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PRODUCTIZATION OF A HIGH-SPEED SOLID ROTOR INDUCTION MOTOR PROTOTYPE

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology

Espoo, September 8, 2014

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Abstract of master's thesis

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Abstract

Productization is the art of developing a customized product, service or prototype into a standardized marketable and commercialized product. In this thesis a high-speed induction motor prototype is designed for manufacturing. The motor has an output power of 86 kW, rotational speed of 21000 rpm and IEC frame size 160. The motor has a copper coated solid rotor concept, hybrid bearings and a totally enclosed air cooling system.

High-speed motor systems provide advantages as improvement of over-all efficiency and reliability in comparison to conventional systems by eliminating the gear box normally used for applications requiring high-speed. In the literature study mechanical restrictions and design considerations due to high rotational speed and centrifugal forces on machine elements are reviewed. Different machine elements are presented as alternatives for high-speed motor components.

To construct a profitable product from manufacturing point of view a concurrent engineering philosophy and DFMA method is adopted. The system of hybrid bearings was retained and the bearing support parts design was reconstructed by reconsidering necessity of the tolerances and altering unnecessarily tight tolerances. It was decided that the bearing end shields and the motor frame foot should be incorporated into one part and produced by casting iron in serial production. Prototype evaluation concludes that a standard stator frame can be used and several rotor concepts were evaluated.

The potential for reducing the manufacturing costs of the prototype motor are substantial. However, regarding the rotor concepts more development needs to be done to ensure a functional rotor concept.

Keywords High-speed technology, electric motors, productization, Concurrent Engineering, DFMA, dimensional and geometrical tolerancing

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Diplomityön tiivistelmä

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Työn nimi Suurnopeusmoottorin prototyypin tuotteistaminen sarjatuotantoon

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Tiivistelmä

Työn tavoitteena oli tuotteistaa suurnopeussähkömoottorin prototyyppi sarjatuotantoa varten. Lähtökohteena oli 86kW:n suurnopeusmoottori, jonka pyörimisnopeus on 21000 r/min ja IEC runkokoko 160. Moottorilla on kuparipinnoitettu massiiviroottori roottorikonseptina, hybridilaakereita ja ilmajäähdytys.

Suurnopeusteknologia mahdollistaa paremman kokonaishyötysuhteen ja kestävämmän järjestelmän poistamalla perinteisesti käytetty vaihteisto suurta pyörimisnopeutta vaativissa sovelluksissa. Suuri pyörimisnopeus ja keskipakovoimien vaikutus suurnopeusmoottorissa aiheuttaa mekaanisia rajoituksia sekä erilliskomponenttien tarvetta. Kirjallisuustutkimuksessa esitellään eri komponenttivaihtoehtoja suurnopeusmoottorin kone-elimistöön.

Tuotteistamisprojektissa käytetään rinnakkaissuunnittelun ja DFMA:n periaatteita. Laakerointiosien toleranssien tarkkuus sekä roottorikonsepti on arvioitu uudestaan ja laakerikilvet ovat yhdistetty staattorirungon jalkaan. Standardistaattorirunko sekä alunperäiset hybridilaakerit soveltuvat käytettäväksi sarjatuotantomoottorissa prototyyppimoottorin evaluoinnin mukaan.

Moottorin sarjatuotannon kustannukset ovat merkittävästi pienempiä verrattuna prototyyppimoottoriin tuotantokustannuksiin, mutta tarvitaan kuitenkin lisätuotekehitystä saavuttaakseen kannattavan hintalaatusuhteen.

Avainsanat Suurnopeustekniikka, sähkömoottori, tuotteistaminen, rinnakkaissuunnittelu, DFMA, mitta- ja geometrinen tolerointi

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Madeleine Bernas

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LIST OF SYMBOLS

A	Area
C	Constant
D	Diameter
E	Young's modulus
I	Moment of inertia
K	Constant estimated from quality loss of a part
k	Ratio between critical frequency and nominal angular velocity
k_{safe}	Safety factor for mechanical stress
$L(Y)$	Quality loss for dimension Y
L_r	Rotor length
n	Rotational speed
P	Power
P_{Cu}	Ohmic loss not depending on frequency
$P_{Cu,r}$	Rotor copper losses
$P_{Cu,s}$	Stator copper losses
P_{exc}	Excess losses
$P_{Fe,r}$	Rotor iron losses
$P_{Fe,s}$	Stator iron losses
$P_{fr,bearings}$	Bearing friction loss
$P_{fr,total}$	Total friction loss
P_{in}	Input power
P_L	Total loss
P_{out}	Output power
P_δ	Air gap power
p_e	Eddy-current loss coefficient
p_f	Friction loss coefficient
p_h	Hysteresis loss coefficient
r	Radius
T	Torque
V_{rt}	Rotor volume
v	Velocity

X	Dimension
Y	Dimension
σ	Maxwell's stress tensor
σ_{max}	Maximum stress allowed
σ_{tan}	Tangential stress
ν	Poisson's coefficient
ρ	Mass density
Ω	Mechanical angular velocity
Ω_C	Critical mechanical angular velocity
Ω_n	Nominal mechanical angular velocity

LIST OF ABBREVIATIONS

AMB	Active Magnetic Bearing
CE	Concurrent Engineering
DFA	Design for Assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacture and Assemly
DFX	Design for X
emf	Electromotive force
HIP	Hot isostatic pressing
IM	Induction motor
IPM	Interior Permanent Magnet
mmf	Magnetomotive force
PM	Permanent magnet
rpm	Revolutions per minute
SPM	Surface-mounted Permanent Magnet
TEFC	Totally enclosed fan cooled
TEWAC	Totally enclosed water to air cooled

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LITERATURE STUDY

1 INTRODUCTION

1.1 BACKGROUND

There is a clearly growing demand for cost efficient, reliable high-speed motors in the low voltage motor market. The actual market trend is towards continuously improving efficiency and power density combined with reduced production costs. Considering motor design trends the direction is to higher and higher rotational speeds with specific interest in direct-drive solutions. (Boglietti et al., 2010)

High-speed technology has been rapidly developing during the recent years and offer several advantages in comparison to conventional methods to achieve high rotational speed and shaft power. High-speed motors are more efficient, demand less maintenance and space than traditional gear systems. High-speed motors also offer higher power density and decreased installation space for higher power.

The construction of high-speed motors differs from conventional induction motors since the components of high-speed motors need to withstand greater centrifugal forces leading to high mechanical stresses on rotating parts. High quality motor elements and special design methods need to be used in high-speed motors to avoid failure and achieve an acceptable life expectancy.

Solid-rotor induction motors are mechanically very stable and therefore a good option for high-speed machines. Other machine constructions, like permanent magnet motors, offer better electromagnetic characteristics. (Arkkio, Jokinen & Lantto, 2005) However in comparison to other machine types, induction motors offer qualities as inexpensiveness, easiness to manufacture and safety. (Pellegrino et al., 2012)

The high-speed market is still quite small and highly efficient production lines do not exist. (Arkkio, Jokinen & Lantto, 2005) This would be the next step in the development.

1.2 RESEARCH OBJECTIVES

An existing motor prototype is to be further developed for serial production. The prototype motor is a high-speed induction motor with rotational speed of 21 krpm and output power of 86kW. The machine has a solid rotor with copper coating by explosion welding and hybrid ceramic bearings. Internal air cooling and forced oil lubrication is applied to the machine. The production cost need to be optimized; prototype needs to be designed for manufacturing. The main research problem of this study is:

- *Can we construct a product which is profitable from a view of manufacturing technology and satisfies quality demands?*

The main objective can be derived from the research problem; to achieve a serial production cost that is sufficient to be able to compete on the high-speed device market against conventional motors with gear boxes.

1.3 RESEARCH SCOPE AND LIMITATIONS

In this research the scope is on the mechanical design of high-speed induction motors with solid rotors. The focus lies on further product development of a high-speed induction motor prototype for serial production. Three main types of high-speed electrical machines are used in the industry: induction machines, permanent-magnet machines and switched-reluctance machines. In this thesis mainly high-speed induction motors are discussed. The starting point for the project is a prototype motor, hence motor concept design is quite clear already and design activities are restricted to system level design and detail level design. Rotor concept however, is discussed. Only the mechanical design aspects of the design process are covered excluding the electrical design aspects.

1.4 RESEARCH METHODS

Research methods utilized are conducting interviews with manufacturing experts, evaluation of possible production methods and materials, determining less strict geometric and positional tolerances for the motor, consideration of possible design alternations that would make the motor more suitable for serial production. New prototype parts are manufactured for design evaluation and cost estimation.

1.5 THESIS OUTLINE

The remaining part of this thesis is organized as following:

- A literature part involving three chapters. Chapter 2 consists of a general brief on high-speed systems; definition, fields of application and advantages of high-speed technology. Chapter 3 present a general study of high-speed solid-rotor induction motors, including the elements used in high-speed solid-rotor induction motors and design considerations for the different machine components. Chapter 4 examines the theory necessary for the design work; design methodology, including general product development process, concurrent engineering, design for manufacturing process and tolerancing.
- A design part consisting of six chapters. Chapter 5 includes project definition, presentation of the high-speed induction motor and cost estimation by cost breakdown structures for the prototype motor and a comparison with a standard motor. Chapter 6 presents the rotor prototype and rotor concept alternatives. Chapter 7 and 8 present the bearing arrangement and the end shields, including design alternations carried out. Chapter 9 presents stator and stator frame. Chapter 10 concludes the thesis with summary of results, discussion, conclusion and recommendations for further work.

2 HIGH-SPEED TECHNOLOGY

2.1 INTRODUCTION TO HIGH-SPEED TECHNOLOGY

High-speed technology research in Finland began as collaboration between Helsinki University of Technology (HUT, today Aalto University), Lappeenranta University of Technology (LUT) and the Finnish Funding Agency for Technology and Innovation (TEKES) in the 1980's. This collaboration resulted in the first high-speed motor prototypes in Finland. During the last three decades a great deal of research on high-speed technology has been conducted and several high-speed technology products and companies have been established. (Larjola, Arkkio & Pyrhönen, 2010)

The need for high speed technology comes from the fact that certain kind of load machine need high rotational speed to perform with high efficiency; the performances of the devices improve with speed e.g. turbo compressors. (Lähteenmäki, 2002; Antila, 1998)

2.2 HIGH-SPEED SYSTEMS

There are several definitions for the expression "high-speed". According to Larjola, Arkkio & Pyrhönen (2010) high-speed technology implies an arrangement where an electrical motor or generator and a regulating load-machinery unit are connected directly to the shaft without gear in between and where the rotational speed of the rotor clearly exceeds 3000 rpm, typically 10 000 rpm. Oil free gas or magnet bearings or special high-speed bearings are used in high-speed devices.

Frequency converters are used to control the speed and power of high-speed devices, this gives full speed control for the drive. (Kolondzovski, 2010) Modern-day frequency converters do not anymore restrict the power of a high-speed drive. The factors that limit maximum power and speed of an electrical high-speed application are mechanical stresses on the rotating parts as well as electrical and thermal issues that increase with frequency. (Boglietti et al., 2010; Arkkio, Jokinen & Lantto, 2005)

High-speed devices are used as electromechanical converters in numerous industrial applications such as (Boglietti et al., 2010; Antipov & Danilevich, 2007; Binder & Schneider, 2007)

- compressors and turbochargers
- blowers
- centrifuges
- turbo-molecular vacuum pumps
- generator motor units for flywheels
- spindles for machine tools
- micro co-generation gas turbines

In Figure 1 an application environment for a high-speed induction motor is shown.

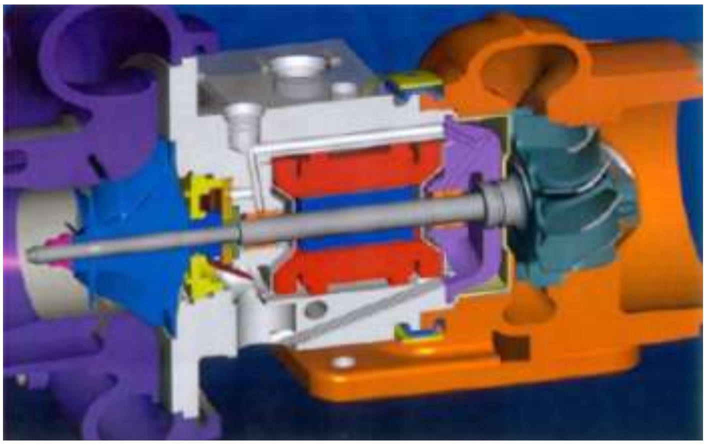


Figure 1. High-speed induction motor used in an automotive environment (Gerada et al., 2011).

2.3 ADVANTAGES OF HIGH SPEED SYSTEMS

In high-speed systems the load-machinery is, as previously mentioned, directly attached to the shaft of the electrical machine, implying a gearbox used in traditional systems for controlling speed is not needed. One of the main advantages of a high-speed motor is this absence of a gearbox, in other words a direct drive. (Huppunen, 2004) Direct drive offer multiple advantages over gears, giving reason to many of the advantages of high-speed systems. (Boglietti et al., 2010)

The size of the electrical motor is determined by the size of the cooling system and the torque according to $P=2\pi \cdot n \cdot T$; hence increasing speed and maintaining the power constant results in lower mechanical torque. Therefore electrical high-speed motors are rather small due to the low torque at high speed if maintaining the power constant. (Binder & Schneider, 2007)

High-speed systems offer advantages in comparison to conventional high-speed systems that include (Boglietti et al., 2010; Kolondzovski, 2010; Binder & Schneider, 2007):

- high power density
- smaller volume and mass
- avoidance of mechanical transmissions
- increased reliability
- system efficiency increase
- reduced maintenance operation costs
- increased mechanical stiffness
- lower noise
- reduction of wear
- oil free performance possibility

Advantages of direct drive in a compressor system are illustrated in Figure 2.

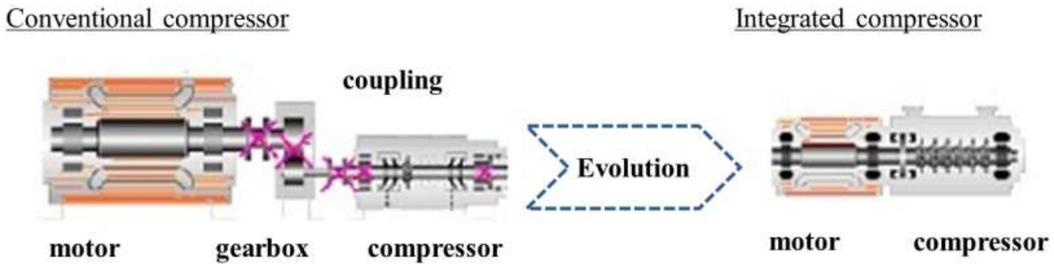


Figure 2. Advantages of using a high-speed system over a conventional system include reduction of system mass and volume. (Lateb, Enon & Durantay, 2009)

High-speed operation brings multiple advantages for several technical processes such as: smaller size for similar power rating in compressors, pumps and gas-turbines, raised cutting speed in cutting and milling, reduced cutting time and improved performance and increased stored energy in flywheels (Binder & Schneider, 2007)

3 HIGH-SPEED MOTORS

3.1 HIGH-SPEED MOTORS IN GENERAL

The induction motor is also the most common machine used for high-speed applications, followed by permanent magnet and switched reluctance machines. Induction machines are adopted in high-speed applications due to their robust rotor structures and low maintenance. (Boglietti et al., 2010)

Rotor joule losses present in induction machines cause the motors to have lower efficiency than other types of electrical machines. Switched Reluctance motors have the most simple and robust rotor structures suitable for high-speed operation and Permanent Magnet motors usually have higher power density and higher efficiency, but both motor types have some drawbacks that could limit their use in high-speed applications. (Boglietti et al., 2010)

3.2 DESIGN CONSIDERATIONS FOR HIGH-SPEED MOTORS

In high-speed applications mechanical aspects are of greater importance than in normal speed machines and therefore require certain design considerations. Mechanical design compromises stress analysis and rotordynamic analysis, involving selection of bearing type, bearing stiffness, shaft diameter and calculation of the rigid and nonrigid body modes of the motor. (Gerada et al., 2011)

High-speed motors are associated with many benefits but also with many problems. By increasing speed and decreasing size, mechanical constraints and machine overheating become main design problems. High-speed devices must sustain large mechanical stress due to centrifugal forces, which cause tangential stress in rotating cylinders or rings. The small machine dimensions and high fundamental frequencies fuel thermal constraints following high losses in the rotor and in the air gap. (Gerada et al., 2011)

Figure 3 illustrates the constraints on a high-speed machine solid rotor.

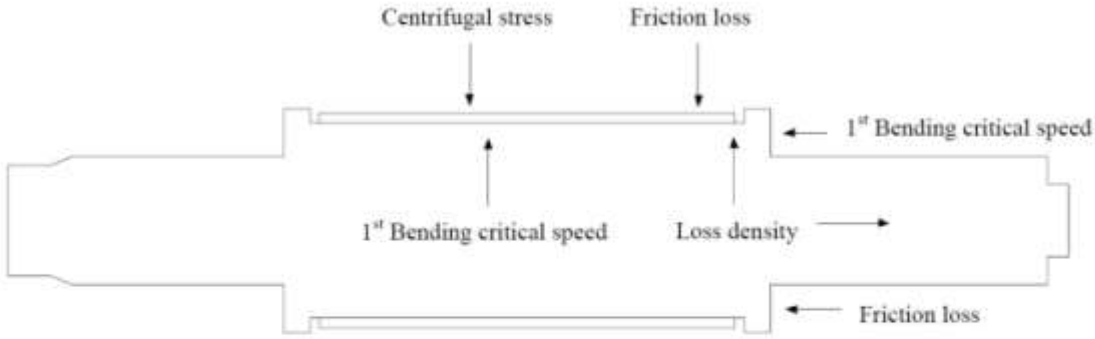


Figure 3. Mechanical and thermal constraints set on the rotor. (Lähteenmäki, 2002)

These constraints affect the choice of material as well as rotor length/diameter ratio and the choice of cooling system. The mechanical constraints often dominate rotor design since they give limits to the size of the rotor and set requirements for manufacturing techniques. Mechanical as well as thermal constraints are often affected by the end application. (Lähteenmäki, 2002)

Typical design features for high speed motors are low iron magnetic flux density values to reduce losses as well as using laminations. The material need to be in safe thermal operating limits and mechanical analysis of material properties as a function of temperature needs to be done to ensure safe operation. (Gerada et al., 2011) The high frequency supply of the motor needs an inverter with low losses. There is also a problem with bearing lifecycle to be solved and the machine mounting needs exact alignment. (Larsson et al., 2003)

3.2.1 ROTOR DIAMETER

The rotor plays an important role in all motor design since the rotor is the interface for transferring mechanical power from the electrical machine to the mechanical load. Normally, the bigger the mechanical torque to be transferred the bigger is the shaft diameter, the torque developed by the electrical machine is proportional to the rotor diameter. (Boglietti et al., 2010) The relation between the torque and the volume can be calculated with help of the electromagnetic rotor surface tangential stress σ_{tan}: (Aho, 2007)

$$T = \sigma_{tan} 2\pi r^2 L_r \tag{3.2.1}$$

The maximum rotor diameter is affected by the rotor surface tangential stress σ_{tan} on the rotor and the mechanical strength of the material. Increasing the diameter increases the torque. However the centrifugal forces increase with rotor diameter and the rotor has to withstand higher mechanical stress. The maximum tangential stress in the rotor takes place in the center of the rotor and is dependent on mass density and circumference speed according to (3.2). (Aho, 2007)

$$\sigma_{max} = C\rho r^2 \Omega^2 \tag{3.2}$$

where ρ is the mass density of the material, Ω is the angular velocity of the rotor, C is a factor that can be estimated:

$$C = \frac{3+\nu}{8} \quad \text{(smooth homogenous cylinder)} \tag{3.3}$$

$$C = \frac{3+\nu}{4} \quad \text{(cylinder with small bore)} \tag{3.4}$$

$$C \approx 1 \quad \text{(thin cylinder)} \tag{3.5}$$

where ν is the Poisson’s coefficient for the corresponding material.

Since $v = r\Omega$ the formula can be written as $\sigma_{max} = C\rho v^2$ where v is the circumference speed, therefore the term “high-speed” is not a matter of high *n* or Ω, more of high *v* as in surface velocity of the rotor. (Binder & Schneider, 2007)

In high-speed machine rotor design the aim is to keep the rotor external diameter as low as possible in order to reduce the peripheral rotational speed and to avoid large centrifugal forces acting on the rotor. Instead the rotor axial length is increased to develop a specific mechanical torque. This also creates a reduction of the friction losses in the air gap, which are significant losses in high-speed machines. Friction losses are proportional to rotor axial length and function of the fourth power of the external diameter. (Boglietti et al., 2010)

The maximum diameter for a solid rotor can be calculated by the formula: (Lateb, Enon & Durantay, 2009, Lähteenmäki, 2002)

$$D_r \leq \sqrt{\frac{8\sigma_{max}}{\rho\pi^2 n^2 (3+\nu)}} \tag{3.6}$$

and for a hollow (laminated) rotor:

$$D_r \leq \sqrt{\frac{4\sigma_{max}}{\rho\pi^2 n^2 (3+\nu)} - \frac{1-\nu}{3+\nu} d_r^2} \tag{3.7}$$

These equations indicate that solid rotors are capable of withstanding higher circumferential speeds than laminated rotors. (Lähteenmäki, 2002)

3.2.2 ROTOR LENGTH

The axial length is limited by the rotor critical speeds, the natural frequencies of the rotor need to be taken into account. If the rotor is operating near critical speed the unbalance coincides with the natural frequency of the motor and the rotor might start to exhibit high vibration levels, and is likely going to be damaged. The damping capacity of the system is low in robust solid rotor constructions and the critical frequencies are inherently high. The maximum rotor length can be estimated from: (Aho, 2007, Pyrhönen 1991)

$$L_r^2 = n^2 \frac{\pi^2}{k\Omega} \sqrt{\frac{EI}{\rho A}} \tag{3.8}$$

where A is the cross-section of the cylinder, n is the ordinal of the critical speed, E is Young's modulus and I is the modulus of inertia. k is a variable defined as the ratio between the n^{th} critical frequency and the nominal angular velocity

$$k = \frac{\Omega_C}{\Omega_n} \tag{3.9}$$

The ratio between the rotor length L_r and the radius r can be estimated with the following formula:

$$\frac{L_r}{r} = n\pi \sqrt{\frac{k_{safe}}{k} \sqrt[4]{\frac{CE}{4\sigma}}} \tag{3.10}$$

where k_{safe} is the safety factor for the maximum mechanical stress. To achieve high speeds without vibrations, thick and short rotor constructions are preferable, and to be absolutely sure, the first critical speed should be above the motor operating speed. High speed machines are often operated between the first and second critical speed, and in high-speed drive systems the rotor might pass several critical speeds during start-up, however the critical speed must be passed by quickly and the speed range is reduced into a narrow speed area. (Boglietti et al., 2010, Aho, 2007)

3.3 INDUCTION ROTORS

One of the most elementary types of rotating machines is an induction or an asynchronous motor. Electric induction motors are the most common source of mechanical power. Properties of induction motors are low cost, reliability and ease of operation. (Lähteenmäki, 2002)

3.2.3 LAMINATED INDUCTION ROTORS

In conventional induction motors laminated rotors are used. The mechanical strength of the electrical silicon steel in standard laminated rotors limit the surface speed to 150 m/s, at higher speeds there is a mechanical problem keeping the lamination layers tightly attached to the shaft. Hence laminated rotors are not rigid enough for higher speeds and more rigid rotor constructions, such as solid rotors, need to be used in high-speed applications. (Aho, 2007)

Figure 4 displays speed limits for laminated and solid rotor types. The curves are obtained using conventional electric and magnetic loadings. There rotors are steel rotors with 700 MPa yield stress with maximum operating speed set at 20 percent below the first critical speed. (Huppunen, 2004)

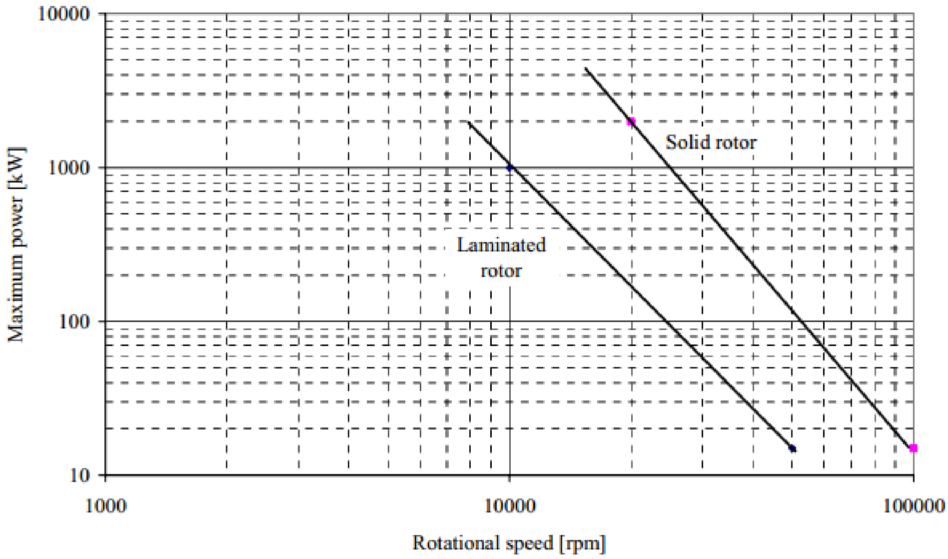


Figure 4. Maximum power versus rotational speed (Huppunen, 2004)

The rotational speed limit for the laminated rotors varies from ca. 10 000 rpm to 50 000 rpm according to Figure 4. However, this speed level might require special construction of the rotors. The rotational speed for solid rotors varies between 20 000 rpm to 100 000 rpm. The upper speed is always set by mechanical restrictions while the output power is defined by the thermal design of the machine. (Huppunen, 2004)

3.2.4 SOLID ROTORS

The solid rotor is ideal in the aspects of fluid dynamical and mechanical performance, and it has very good thermal resistance. This rotor type is the strongest possible, most stable and maintains its balance best of all rotor types. Maintaining balance and avoiding vibrations is important to not cause damage to the bearing system. (Huppunen, 2004) Solid rotors can stand surface speeds larger than 400 m/s (Arkkio, Jokinen & Lantto, 2005) are used for rotational speeds between 20 000-200 000 rpm and where the rotor surface speed exceeds 150 m/s. (Saari, 1998) Solid-rotors are built with a rotor core made of a solid single piece of ferromagnetic material. The solid rotor is an easy and cheap alternative from a manufacturing point of view. (Aho, 2007)

The solid rotor construction offer several advantages such as: (Huppunen, 2004)

- High mechanical stability
- High thermal strength
- High reliability
- Easy and cheap to manufacture
- Easy to achieve high chemical durability
- Low noise and vibration level (if the surface is smooth)

Electrical properties of smooth solid rotors are poor due to the generation of excessive eddy-current losses in the solid rotor surface. (Aho, 2007) The output power, efficiency and power factor for a solid-rotor induction motor is lower than for a laminated rotor cage induction motor. These factors can be diminished in one of the following ways: (Huppunen, 2004)

a) Constructing the solid rotor of a material with a small ratio of magnetic permeability to electric conductivity.
b) Using axial slits to improve the magnetic flux penetration to the rotor material.
c) End-ring structure of high-conductivity material.
d) Embed a squirrel cage in the rotor material.
e) Coating the rotor.

These alternatives are illustrated in Figure 5.

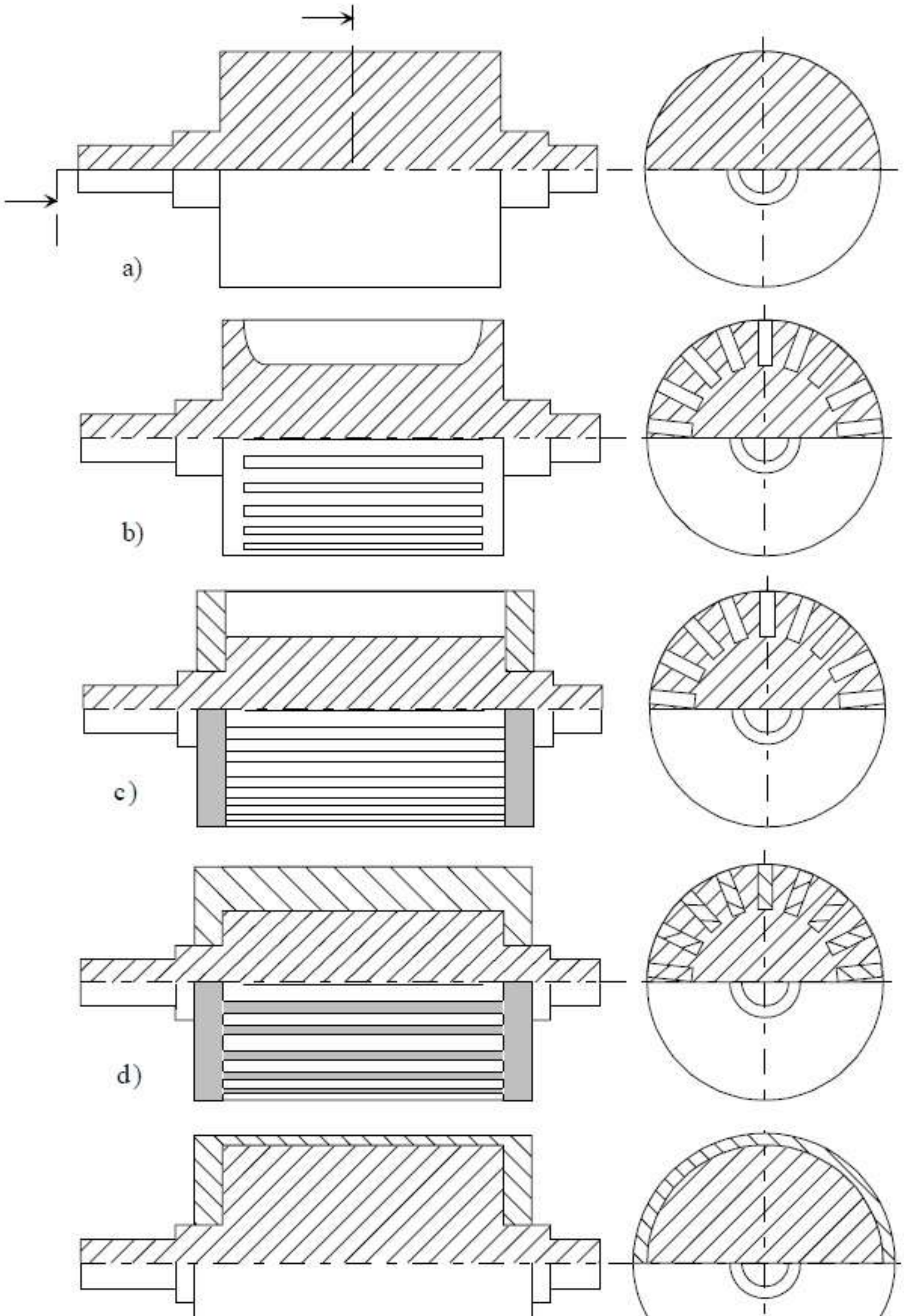


Figure 5. Solid-rotor designs: a) smooth solid rotor, b) axially slitted solid rotor, c) axially slitted solid rotor with end-ring structure, d) solid rotor with deep copper bars and end rings (squirrel cage), e) smooth solid rotor with coating. (Huppunen, 2004)

The easiest performance improvement method seen in Figure 5 b) **is slitting the cross-section of the rotor**, to achieve better flux penetration into the rotor. Slitting the rotor decreases low-frequency impedance in the rotor, therefore more torque is produced. Slitting also increases the high-frequency surface impedance on the rotor, decreasing eddy-current loss. The disadvantage of axial slitting is the fact that the ruggedness of the solid rotor is to a part lost and at very high speeds the friction between the rotor and air is remarkably increased. The slitting increases the cooling of the rotor because of increased cooling surface, so increased friction might be justified by this in medium speed motors (10 krpm) but not high speed motors. (Aho, 2007)

End rings, seen in Figure 5 c), could be used to reduce the rotor impedance and improve the torque and power factor of the machine. Very precise manufacturing is required to produce this kind of rotor. The copper end rings must have a tight galvanic connection to the solid rotor end. If there is any gap between the rotor base material and the end rings, the end ring effect will be lost and there might be dangerous vibrations at high-speed. This rotor type has lower ruggedness and cannot be used with an aggressive medium. (Uzhegov, 2012)

A solid rotor type with **copper squirrel cage** is shown in Figure 5 d). This type of rotor has the best performance, but the squirrel cage with deep copper bars is difficult to produce. The mechanical ruggedness can suffer from the construction and also this rotor type cannot be used in an aggressive medium. (Uzhegov, 2012)

As seen in Figure 5 e) the **outer layer of the rotor can be laminated** with high-conductive low permeability material (like copper) to reduce the eddy current losses in the surface. The coating material acts as a mirror for high-frequency air gap harmonics and does not let high-frequency harmonics penetrate through the laminated layer. Copper coating is good from an electromagnetic performance point of view, however it should be noted that producing a copper coating on a solid rotor is expensive. Another method is to coat the rotor with high-resistive ferromagnetic material. The idea in this approach is that the coating should increase the rotor surface impedance and dampens the harmonic fields before they reach the rotor core material and create losses. If using this method the coating might be welded onto the rotor, which would boost the rigidity of for instance a solid slitted rotor. (Aho, 2007)

3.4 SYNCHRONOUS ROTORS

The synchronous motor operates as the name suggests at a synchronous speed determined by the stator excitation frequency. (Haataja, 2003) There are three main types of synchronous rotors, these are depicted in Figure 6.

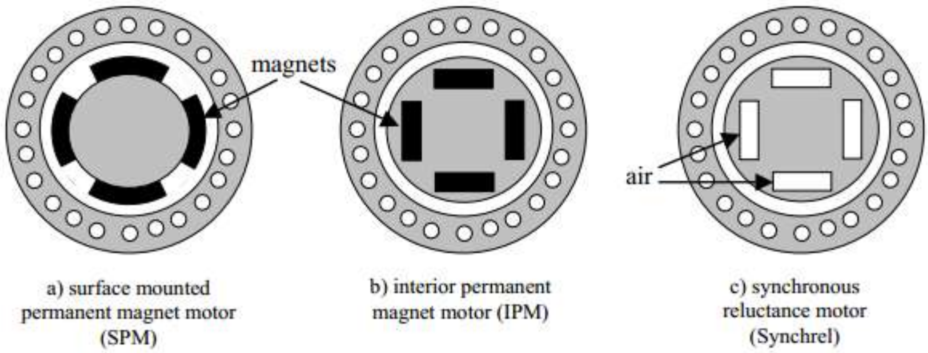


Figure 6. Cross section of three main synchronous motor types. (Meier, 2002)

Figure 6 a) shows the cross section of a surface mounted PM. Machine. Permanent magnets are fixed to an iron rotor core, normally glued to the rotor surface and bandaged with e.g. glass-fibre to ensure mechanical strength standing centrifugal forces. Figure 6 b) shows a possible design of an interior permanent magnet motor. The magnets are buried into the rotor core. Setting the magnets inside improves the mechanical stability of the rotor and the magnetic protection. Figure 6 c) shows a cross section of a reluctance rotor, without permanent magnets, the reluctance motor only produces reluctance torque. (Meier, 2002)

3.2.5 PERMANENT MAGNET ROTORS

Permanent magnet motors differ from induction motors by the fact that the magnetic field is produced by the rotor and not the stator windings. The magnetic field is produced by the permanent magnets in the rotor and arranged to drive flux across the air gap in alternating directions into and out of the rotor surface. Constant torque is produced when the pattern of flux on the rotor revolves in perfect synchrony with the rotating field produced by the stator. (Beer et al., 2006)

Permanent magnet motors can be of the types surface-mounted PM (SPM) and interior PM (IPM). The SPM motor has a simpler construction and shorter end connection but has eddy-current loss at high-speed, very limited transient overload power, and has high uncontrolled generator voltage. The IPM motor has better performance, but is more complicated to manufacture. (Pellegrino et al., 2012)

Internal permanent magnet rotor construction consists of a shaft of solid steel with permanent magnets mounted onto the shaft. On and between the permanent magnets is an aluminium screen to reduce eddy-current losses. To support the system from centrifugal forces a carbon fibre sleeve or retaining ring is used. (Arkkio, Jokinen & Lantto, 2005) An example of a permanent rotor construction is depicted in Figure 7.

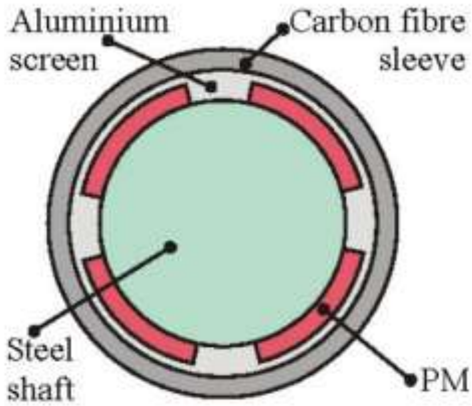


Figure 7. Example of Permanent Magnet rotor construction. (Arkkio, Jokinen & Lantto, 2005)

Permanent magnet (PM) motors are considered to have higher efficiency and higher torque in comparison to induction motors. However, mechanical constraints limit the use of PM machines to applications with surface speeds under 250 m/s. When designing PMs the eddy-current loss of the rotor and permanent magnets need to be minimized. These losses easily induce temperature rise higher than allowed in the permanent magnets. (Arkkio, Jokinen & Lantto, 2005)

3.2.6 RELUCTANCE ROTORS

The electromagnetic torque for synchronous reluctance motors only consists of reluctance torque. The principle for producing the torque is using reluctance differences.

(Haataja, 2003) The reluctance motor is constructed based on the principle that a magnetic field will exert a force to decrease the resistance to the flow of magnetic flux. The reluctance rotors do not produce their own magnetic field, rather providing a position dependent reluctance known as magnetic saliency. There are two types of reluctance motors; the switched reluctance motor utilizing a stator that also possesses magnetic saliency and the synchronous reluctance machine that contains a similar stator to that used in an AC induction motor. (Hortman, 2004)

3.3 STATOR

The most important design aspect in the design of high-speed rotor is perhaps having a smooth sinusoidal air gap flux at the surface of the rotor. If the air gap flux is not smooth the harmonic components will induce a considerable amount of loss on the rotor, especially in solid rotors. (Lähteenmäki, 2002)

There are currently two approaches for reducing the harmonic losses. One approach is making the magnetomotive force (mmf) produced by the stator windings as sinusoidal as possible, aiming to reduce the winding harmonics. Another approach is making the air gap permeance as smooth as possible. Both approaches can be applied at the same time to reduce the harmonic content of the air gap flux. (Lähteenmäki, 2002)

Smoother mmf waveform can be achieved by an increased number of slots or by using a chorded two layer winding instead of one that is used in conventional motors. As a ground rule, the more slots the better, if they do not become too small and there is room enough for the teeth. This reduces the losses in the rotor side, and the reduction is usually enough to cover the increase of iron loss at the stator side that follows the increased slot number. (Lähteenmäki, 2002)

The stator design can also be improved by using a short pitch double layer winding. The pitching decreases the harmonic contents of the mmf and the air gap flux efficiently. However, main voltage insulation is needed between two phases in the same slot, leading to a decrease of the slot filling factor. The winding factor for the magnetomotive force is also reduced slightly. (Lähteenmäki, 2002)

The high frequency currents and stray flux may cause skin effect and eddy-current loss in the windings. This can be avoided by using random wound windings, consisting of thin conductors. Another design problem is the fact that rotor dynamics often suggest a short but wide rotor construction, hence the same for stator. For a two pole motor this results in higher ohmic loss and leakage inductance due to long end windings. A four pole motor would be better, but this would mean double supply frequency, higher iron loss, increased skin effect and higher switching loss for the inverter. A design trade off decision has to be made. (Lähteenmäki, 2002)

Stator design is especially important in solid rotor machines due to the fact that harmonic eddy current losses are a significant problem in solid rotor machines than compared to laminated-rotor machines. Normally, harmonic eddy current losses make up only 2-5% of total losses in laminated rotor machines. However, in the case of solid rotor machines harmonic losses normally constitute 10% of total losses and can reach up to 50% if the motor is not designed properly. High efficiency of the solid-rotor induction motor can be reached if the stator losses and the harmonics in the air-gap are kept low. (Huppunen, 2004)

3.3.1 AIR GAP AND SLOT OPENING

The air gap flux at the rotor side might be the most important single parameter in the whole design of a high-speed motor. The size of the air gap affects the air gap permeance variation a lot and in addition to decreasing winding harmonics the permeance harmonics need to be reduced. (Lähteenmäki, 2002)

For an induction motor a long air gap is a problem since the rotor has to be magnetized from the stator side. A long air gap means high magnetization current, increased ohmic losses in stator windings and lower power factor. On the other hand a long air gap is needed to dampen the harmonic components of the magnetic flux on the rotor surface. The increased need of magnetization can be seen as compensated for by the reduction in rotor loss. (Lähteenmäki, 2002)

The selection of the air gap is based on balancing the loss components so that total loss is minimized. The cooling is also influenced by the size of the air gap if the flow is forced through the air gap. The air gap in high-speed motors is normally larger than in conventional induction motors, and this seems to be the solution for high-speed applications. (Lähteenmäki, 2002)

The other way to decrease the permeance harmonics is to minimize the stator slot opening. Magnetic or semi-magnetic slot wedges close the slot opening and smoothen the permeance fluctuation, but there is a down side with increased leakage reactance. (Lähteenmäki, 2002)

3.4 LOSSES AND COOLING OF HIGH-SPEED MOTORS

High-speed machines need an extremely reliable cooling system, in order to avoid stator winding, rotor cage and bearings overheating and shaft deformations. (Boglietti et al., 2010) The cooling system design is of equal importance as the electromagnetic design of the motor, since the thermal rise of the motor eventually determines the output power of the motor. (Almasi, 2012)

The cooling of a high-speed machine needs to be designed with special attention; the power-size ratio of the machine increases as the rotational speed of the machine increases; the power density as well as the loss density is increased. (Antila, 1998) Figure 8 illustrates the power losses in a high-speed induction motor.

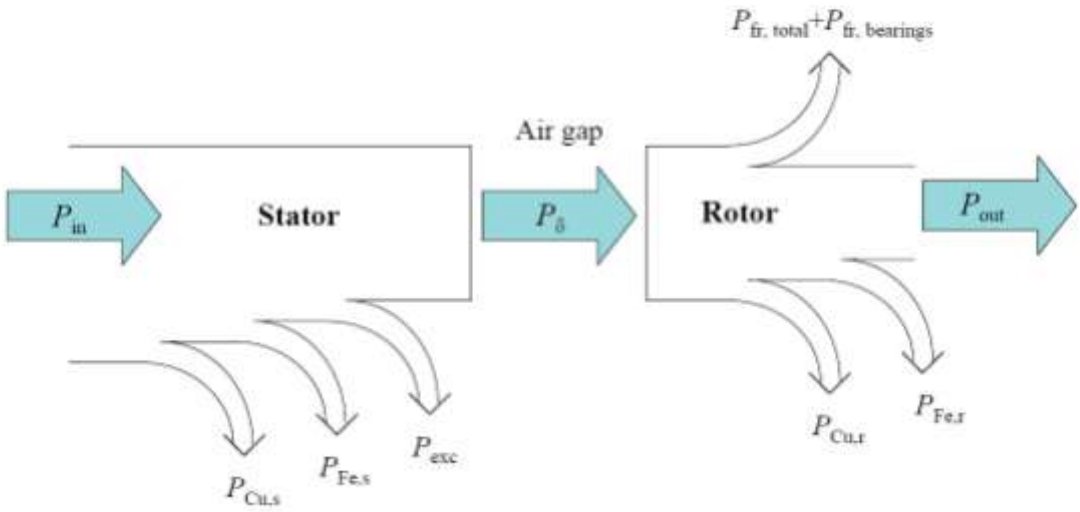


Figure 8. Power losses of an induction motor. (Aho, 2007)

The stator copper losses P_{Cu} and the iron losses P_{Fe} consumes some of the power supplied to the motor, P_{exc} stands for excess losses in the stator. On the rotor side there are resistive losses $P_{Cu,r}$ and iron losses $P_{Fe,r}$. In addition there are mechanical losses caused by bearings, windage and gas friction. The remaining power P_{out} is the value of P_{in} deducted by the losses.

The distribution of the losses is different in a high-speed motor compared to a conventional motor. The relative share of the loss components change with speed according to the following quotient of total loss P_L per output power P_{out} (Lähteenmäki, 2002):

$$\frac{P_L}{P_{out}} = \frac{P_{Cu}+p_h n+p_e n^2+p_f n^3}{CV_{rt} n} \tag{3.11}$$

where P_{Cu} is the ohmic loss not dependent on frequency and p_h, p_e and p_f are the loss coefficients for hysteresis, eddy-current and friction loss. C is a utilization factor describing how much torque per volume unit can be taken out from the rotor of a volume V_{rt}. n stands for rotational speed. According to the quotient the relative share of ohmic losses decreases while the share of eddy-current and friction losses increases with rotational speed. This illustrates how the losses are distributed as a function of speed, implying that a motor design should change with rotational speed. (Lähteenmäki, 2002)

Since high-speed motors have high loss densities, high-speed machines need open-circuit cooling. (Saari, 1998) In high-speed machines normally the cooling substance flows through the motor removing the heat from interior parts. The cooling system is usually a totally enclosed water to air cooled (TEWAC) unit. (Almasi, 2012) Totally enclosed fan cooled (TEFC) motors are not viable for high-speed motors, since the major part of the losses are friction and cooling losses generated in the air gap between stator and rotor. The hot air in the air gap must be taken out. (Lähteenmäki, 2002)

The cooling system of the high-speed motor highly impacts design of the machine and vice versa. Different coolants and cooling flow topologies can be chosen for high-speed motors depending on the motor construction. Design selection of the motor and the cooling system go hand in hand. For instance in some cases direct cooling of rotor is considered troublesome and cooling of stator is utilized instead, cooling of the stator might need axial or radial cooling ducts. Hydrogen or helium can be used as closed circuit coolants, reducing friction loss and increasing heat transfer, while water coolant for stator can be used for maximum performance. (Lähteenmäki, 2002)

During cooling system design for high-speed motors it is important to consider avoiding high thermal differences in certain part of the motor, e.g. around the bearings. Another aspect to consider while designing cooling systems for high-speed machines is the fact that coolant flow through the air gap of the motors could generate losses due to the gas-flow, which can reduce total motor efficiency. (Boglietti et al., 2010)

3.5 HIGH-SPEED BEARINGS

Bearings are critical components in high-speed electrical motor design. Higher rotational speed, stiffness, precision and less noise are required from bearings used in high-speed applications. (Boglietti et al., 2010) Bearings in high-speed technology devices are usually oil free gas- or magnet bearings, or circulating lubrication systems. (Larjola, Arkkio & Pyrhönen, 2010)

The lack of high-speed bearing technologies permitting high reliability and long lifetime is currently limiting a successful application of ultra-high-speed drive systems. (Looser & Kolar, 2011) Conventional roller bearings have a limited life time in high-speed applications. Ceramic bearings are used at higher speeds; however, even these cannot provide particularly long service life. Gas bearings are not widely used in industrial applications, due to a number of factors. There is no readily usable design algorithm for gas bearings, there are instability problems and it is difficult to predict dynamic behavior. Testing the gas bearings is problematic since appropriate test benches are not available. (Belforte et al., 2005) Magnetic bearings are major electromechanical systems with considerable complexity. However, the contact less concepts of magnetic and gas bearing are promising future concepts. (Looser & Kolar, 2011)

3.5.1 ACTIVE MAGNET BEARINGS

The main advantages for active magnet bearings are no friction, no lubrication, precise position control and vibration damping. Active magnet bearings allow higher speed than conventional roller bearings since there is no friction. Friction is eliminated since there is no contact between the static and rotating parts. The speed limit is defined by the AMB rotor mechanical rupture due to the centrifugal force generated by rotation. The use of magnetic bearings also eliminates balancing problems. Mechanically it is impossible to make the bearings rotation axis coincide with the inertia axis of the rotating part exactly, this creates an unbalance can produce vibrations, but magnetic bearings make balancing possible. Magnetic bearings can be used for extreme temperatures, either high temperatures or close to absolute zero, if they are manufactured from adapted materials. (Rodrigues et al., 2008)

In AMB the magnetic forces are utilized to support the rotor without physical contact. The electromagnets pull the rotor to opposite sides, however the interaction between the rotor and electromagnets are unstable. Stable operation is only possible by feedback control: the position of the shaft has to be measured and the currents in the coils have to be controlled for correct positioning. (Antila, 1998) Typically an AMB system compromises a rotor, an electromagnetic actuator, power amplifiers, position sensor and a digital controller. Figure 9 shows a functional diagram of an AMB system. (Myburgh S., van Schoor G. & Ranft E.O., 2010)

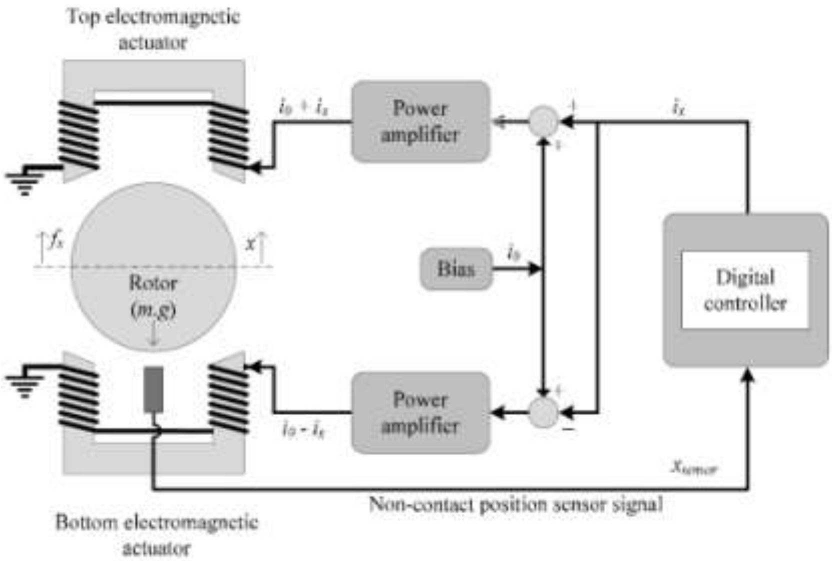


Figure 9. Overview of an AMB system. (Myburgh S., van Schoor G. & Ranft E.O., 2010)

AMB have low specific load capacity in comparison with conventional bearings and a large number of components and sub-assemblies. AMB have lower reliability and high equipment cost due to this number of complex sub-assemblies. There is also a possibility total breakdown of load capacity if one single bearing component fails. The danger of unpredictable machine run down is the major reason for AMB-technology not having a broad industrial acceptance. (Wassermann, Schulz & Schneeberger, 2003)

3.5.2 GAS FOIL BEARINGS

Gas foil bearings are self-acting hydrodynamic bearings made from sheet metal foils with ambient gas as their working fluid. As active magnetic bearings gas foil bearings also offer a contactless rotor system, since they generate a fluid film between the rotating shaft and the top foil. Foil bearings are used in high-speed machines with light load. Figure 10 shows an example of first-generation foil bearings. (DellaCorte et al., 2008)

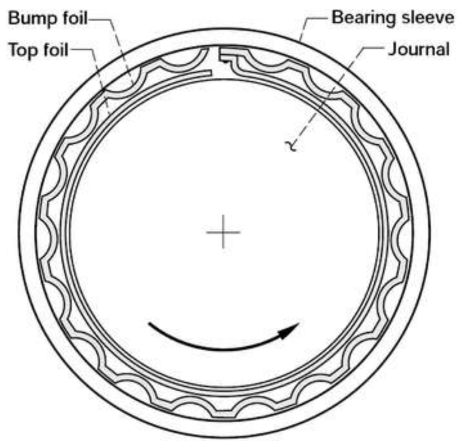


Figure 10. Bump type foil bearing. (Arora et al., 2011)

During machine operation, the rotation of the shaft generates a pressurized gas film that pushes the top foil out radially, making the top foil totally separated from the rotating shaft. The pressure in the air film is proportional to the relative surface velocity between shaft and top foil. The bearing surface is in contact with the shaft when the machine starts and stops. (Arora et al., 2011)

A more compact drive system can be achieved with gas bearings than magnet bearings, since they can be designed smaller than magnet bearings for the same load capacity and stiffness. Another advantage of gas bearings in comparison to active magnet bearings is reduced system complexity; gas bearings do not require position sensors or power amplifiers and control as used in traditional magnetic bearing designs. One major disadvantage with high-speed gas bearings is the self-excited whirl instability that limits the use at high rotational speeds. (Looser & Kolar, 2011)

3.5.3 HYBRID CERAMIC BEARINGS

Hybrid ceramic bearings are used extensively in high-speed applications. Hybrid ball bearings are composed by internal and external steel rings, and low density high stiffness ceramic rolling balls. The most commonly used material in hybrid precision bearings is hot isostatically pressured (HIP) silicon nitride Si_3N_4. (Thoma et al., 2003)

The excellent hardness and light weight of the ceramic material leads to good performance under high temperature since the material properties result in lower friction and therefore less heat generation. (SKF, 1998; Shoda et al., 1997) This is the main advantage of using ceramic ball bearings such as silicon nitride bearings; the reduction of centrifugal loading and smaller gyroscopic moment on the outer raceway due to the low density of silicon nitride balls. (Thoma et al., 2003, Shoda et al., 1997) The density of silicon nitride is ρ_{sn}=3,2 g/cm^3 in comparison to conventional bearing steel ρ_{st}= 7,9 g/cm^3. (SKF, 1998) The heat generation of hybrid bearings is 10 to 20 percent less than all steel bearings and 30 to 50 percent during certain lubrication. (Shoda et al., 1997)

Ceramic materials are also more resistant to corrosion and abrasion than steel. (Thoma et al., 2003) Another advantage with using ceramic material in the bearings is the fact that ceramic materials function as electrical insulators, implying electric currents will not pass through hybrid bearings preventing electricity damage of the machine. (SKF, 1998)

4 DESIGN THEORY AND PRODUCTIVITY DRIVERS

4.1 GENERAL PRODUCT DEVELOPMENT PROCESS

A well-defined process is useful for several reasons such as quality assurance, team coordination, planning, management and room for improvement. Figure 11 depict the generic product development process according to Ulrich and Eppinger (2012).

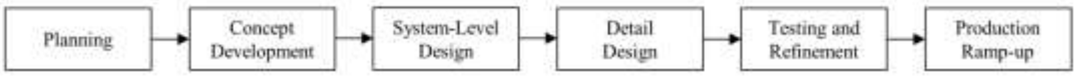


Figure 11. Generic product development process. (Ulrich & Eppinger, 2012)

The generic product development process consists of six phases. The *planning phase* precedes project approval and launch of the actual product development process, therefore this is usually referred to as “phase zero”. *Concept development* is the following phase where the customer needs are identified, product concepts are generated and evaluated. The result is a set of specifications; functional requirements for the product. At *system-level design* phase the product architecture is defined, the product is decomposed into modules and components and preliminary design of key components is done. The outcome can be a geometric layout of the whole product and specifications of different modules. The *detail design* phase includes complete specification of geometry, materials and tolerances for all parts in the product and specification of standard used parts. *Testing and refinement* phase involve construction and evaluation of preproduction versions of the product. The last phase is *production ramp-up* where the product is made in the intended production system. (Ulrich & Eppinger, 2012)

4.2 CONCURRENT ENGINEERING

Concurrent engineering approaches the design problem differently than traditional methods. Product and process design activities interact in a multidirectional type of network, concurrent engineering can impact on both process and product design. The concurrent engineering approach can be seen in Figure 12. (Youssef, 1994)

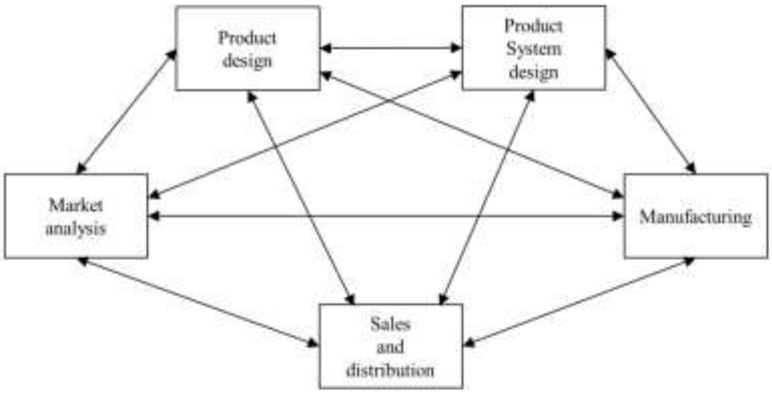


Figure 12. Concurrent Engineering; a nonlinear design approach. (Youssef, 1994)

Concurrent engineering is a nonlinear product design approach; manufacturing phases, concerns and abilities are considered at the same time while designing the product.

Concurrent engineering can also be referred to as simultaneous engineering. There are four Cs of simultaneous engineering: (Youssef, 1994)

1) *Concurrence*. Parallel product and process design occurring in the same time frame.
2) *Constraints.* To ensure that parts are easy to fabricate, handle and assemble process constraints are considered part of product design.
3) *Co-ordination.* Co-ordination of product and process for effective cost, quality and delivery.
4) *Consensus.* Involving full team participation in product and process decision.

A successful implementation of CE demands integration of the four Cs at macro and micro levels; between the manufacturing organization and its external environment as well as between internal components of the manufacturing organization. (Youssef, 1994)

4.3 DESIGN FOR MANUFACTURING AND ASSEMBLY

According to Boothroyd et al. (1994)

> *"Design for Manufacture means the design for ease of manufacture of the collection of parts that will form the product after assembly"*
>
> *"Design for Assembly means the design of the product for ease of assembly"*

DFMA techniques are important tools in the concurrent engineering field. The use of DFMA techniques have resulted in dramatic cost reductions in many products in many cases. (Boothroyd et al., 1994) The goal for DFMA is to reduce manufacturing costs and improve the easiness of the manufacturing process. (O'Drischoll, 2002)

The importance of DFMA comes from the fact that the design of any product is a compromise of conflicting goals. The most important conflict is the conflict of consumer requirements, the price the customer is willing to pay and the cost of rival products. The best compromise can be reached through DFMA, producing a high-performance, competitively priced product at minimal cost. According to current research approximately up to 80% of the manufacturing costs are determined by the design of the product, although design costs consume only 10% of the budget. (O'Drischoll, 2002) Figure 13 illustrates the relation between costs fueled by design decisions and development of expenses during a generic product life cycle.

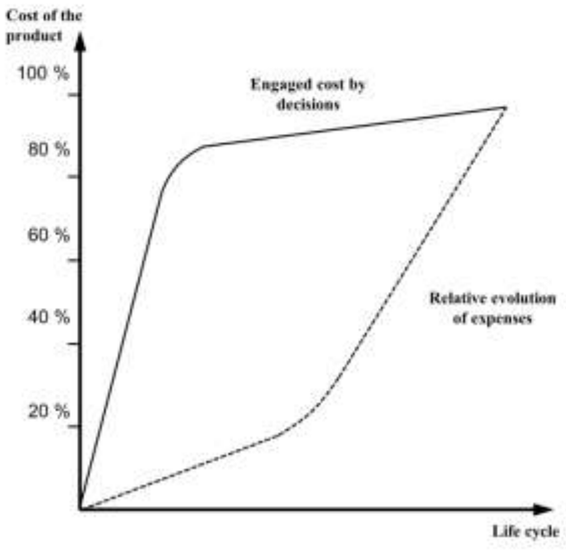


Figure 13. Engaged cost by decisions and evolution of expenses during product life cycle. (Mäkinen, 2010)

The final cost is largely established by decisions made during concept development and design phases; giving different design phases a key role in product development. (Mäkinen, 2010)

Reduction of cost should be done during design phase of the product, not while the product already is in production. Cost reduction efforts after the product is designed may be difficult to achieve; cost is designed into the product and the production process, thus hard to remove later. Utilizing a thinking perspective of total cost is the key to achieve lowest cost possible. Usually companies only take material and labor costs into consideration, although much can be done to lower overhead costs by design. (Anderson, 2008)

DFM compares the manufacturing requirements to existing manufacturing capabilities of a product and measures the processing time and cost. DFM approaches can be used both during conceptual design phase and the detailed design steps. In general DFM approaches put the focus on individual manufacturing operations. DFM is necessary for a successful product development process since it is very useful in reducing the unit cost of manufacturing products. Central questions in DFM are: (Herrmann & Chincholkar, 2001)

- Can the manufacturing process feasibly fabricate the specified product design?
- How much time does the manufacturing operation require?
- How much does the operation cost?

There are several approaches developed to determine the manufacturability of a given design. Most approaches are *direct or rule-based approaches* evaluate manufacturability by direct inspection of design description. Design characteristics improving manufacturability are represented in a set of rules, which are applied to evaluate the manufacturability of given design. *Indirect of plan-based approaches* involve a more detailed analysis, these proceed by generating a manufacturing plan and examine this according to criteria such as cost and processing time. The direct approach seems to be more suitable for e. g. near net-shape manufacturing and less useful for machined and electromechanical components, where interactions between manufacturing operations make it difficult to determine manufacturability of a design directly from design description. (Herrmann & Chincholkar, 2001)

4.3.1 ADVANTAGES OF DFMA

Implementing concurrent engineering and DFMA give rise to benefits such as better-designed, higher quality products and shorter time to market. (Youssef, 1994) Advantages of adopting concurrent engineering and a DFMA strategy are according to Boothroyd et al. (1994):

- Communication improvement between the design and manufacturing department, since the designer is forced to consider manufacturing aspects of the design during the design process.
- Applying DFMA techniques to product design will lead to improved product quality.
- The use of DFMA reduces product development time.
- DFMA provides a systematic procedure for analyzing design by considering manufacturing and assembly. This leads to major savings in manufacturing costs.
- Maintenance efficiency is increased; if a part is easy to assemble, it is easy to disassemble too.

4.3.2 DFMA GUIDELINES

Various design guidelines have been developed for Design for Manufacturing and Assembly (DFMA), with slightly different emphasizes. The following guidelines combine theoretical minimum number of parts and aims to affect higher level product design in early design stages. (Lähtinen, 2011, Zakaria, 2009):

I. **Aim for simplicity** reduces part handling time and assembly operations.
    - Reduce number of production steps and tools, by substituting with an alternative process.

- Minimize part count, by integrating several parts if they do not qualify as theoretically necessary.
- Never design an item that can be catalogue bought.
- Regard subassemblies, especially if they may be separately tested.

II. **Standardized components and processes** are more economic than custom ones, since the unit cost decrease with production volume increase. Standard products are common for more than one product. Standardization can occur within the product line of the company as internal standardization or via an outside supplier, across the product lines of several firms as external standardization. Components can also be standardized within the same model.

III. **Rationalize product design** by standardization of materials, components and subassemblies for an increased economic scale for the part process. Rationalizing the product design also involves modularization and choosing an appropriate economic scale for the part process, since some processes have low fixed costs and high variable costs and vice versa.

IV. **Usage of widest possible tolerances**. Unnecessary tolerances and surface demands are costly and should be avoided on non-critical components.

V. **Choose materials suitable for function and production processes.** Material choice should favor the production process to ensure product quality.

VI. **Minimize handling and other non-value adding operations.** Minimizing unproductive operations reduces costs and lead time for assembly work.

VII. **Design for process:** take advantage of process capability and limitations while designing the product.

4.3.3 THE DFM PROCESS

According to the DFM approach of Ulrich & Eppinger the DFM process consists of five stages and some iteration:

1. Estimate the manufacturing costs
2. Reduce the costs of components
3. Reduce the costs of assembly
4. Reduce the costs of supporting production

5. Consider the impact of DFM decisions on other factors

The process is illustrated in Figure 14.

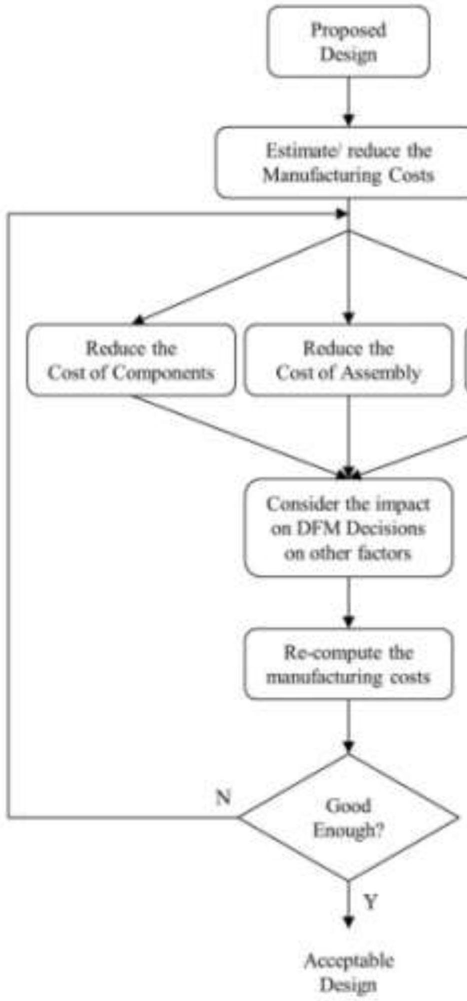


Figure 14. The DFM process. (Ulrich & Eppinger, 2012)

The first step is estimation of manufacturing costs to determine whether components, assembly or support are the most costly, to determine where the attention will be directed in the next step. When estimating component costs for standard parts, production quantities are extremely important. This process is iterative, it is common to recalculate estimated manufacturing costs and improve design several times. (Ulrich & Eppinger, 2012)

4.3.4 ESTIMATION OF MANUFACTURING COSTS

The unit manufacturing costs of a product can be categorized into three categories according to Figure 15. (Ulrich & Eppinger, 2012)

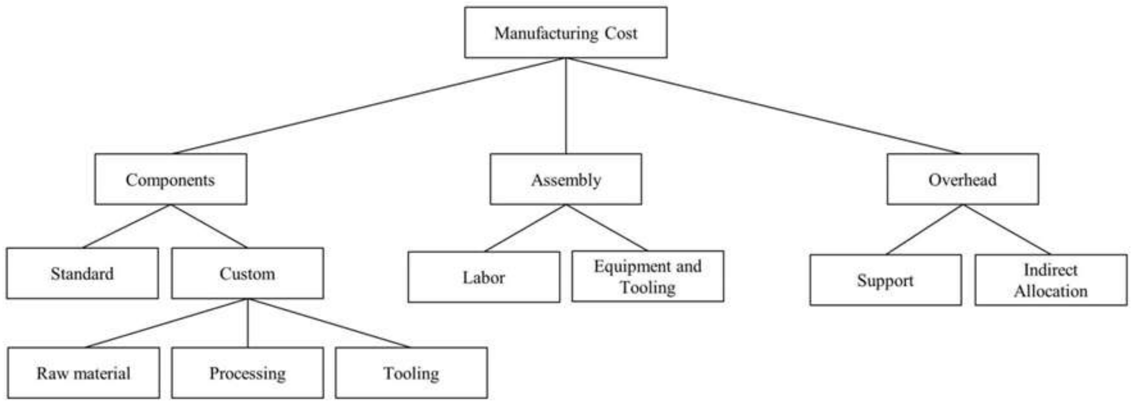


Figure 15. Categorization of manufacturing costs. (Ulrich & Eppinger, 2012)

The component costs of the product include standard parts and custom parts. The assembly costs include labor costs and may also include equipment and tooling costs, while the overhead cost category encompass all other costs. There are two types of overhead costs, support costs and indirect allocations. Support costs are costs associated with materials handling, quality assurance, purchasing, shipping, facilities and so forth, while indirect allocations are costs that cannot directly be linked to the product but need to be there to be in business. (Ulrich & Eppinger, 2012)

The costs can also be divided into fixed costs and variable costs. Fixed costs are costs that do not change depending on amount produced, although no costs are truly fixed, while variable costs are costs that in direct proportion change with produced units. (Ulrich & Eppinger, 2012)

When estimating component costs for standard parts, production quantities are extremely important. Standard parts costs are estimated by soliciting price quotes from suppliers or comparing the component to a substantially similar component produced by the firm. While estimating the costs for custom parts, the costs for raw material, processing and tooling are added up. Processing costs include costs for the operator operating the machinery and for the equipment needed. Tooling costs are for the design and fabrication of cutters, molds, dies or fixtures to use certain machinery to create a part. (Ulrich & Eppinger, 2012)

Assembly costs can be estimated by summing the estimated time of each assembly operation and multiplying by labor rate and software tools can also be used. Estimating overhead costs is difficult. (Ulrich & Eppinger, 2012)

4.3.5 CONSIDERING DFM IMPACT ON OTHER FACTORS

The economic success of a product depends on other factors than manufacturing costs. Quality, timeline of product introduction and cost of developing the product are other objectives in the product development process: (Ulrich & Eppinger, 2012)

- **The impact of DFM on development time** is crucial for some projects. For this reason DFM decisions must be evaluated for their impact on both manufacturing costs and development time. Part complexity induced by DFMA guidelines may lead to excess development time. The same caution about complex part design and development time applies to **DFM impact on development cost**.

- **The impact of DFM on product quality**. DFM methods may cause a quality reduction of the product, while designing for manufacturing, it is important to consider the significance of certain quality dimensions.

- **The impact of DFM on external factors** goes beyond the responsibilities of the development team. Component reuse and life cycle cost are two of these factors. *Component reuse* implies that taking time and money to design a low cost component might be of benefit for other teams designing similar product but actually more costly for the product. *Life cycle costs* are company or societal costs not accounted for in the manufacturing process, e.g. special handling and disposal, service and warranty costs, which should be of importance in a DFM decision.

4.4 TOLERANCES

Tolerancing is a vital part of design for manufacturing. Manufacturing methods are limited in their capabilities. Process variations influence the physical realization of the product; this is expressed as deviation in geometry and shape. Deviations in physical characteristics influence the performance of the part. To solve this problem, tolerances are used. (Srinivasan, 1994)

The term tolerance refers to allowable deviation of a dimension from the specific basic size. The proper performance of a machine is dependent on tolerances specified for its components, especially when it comes to mating components and parts in relative motion. Considering tolerances and fits is important in power transmission elements as well as bearing housings. (Mott, 1999) Tolerances are set to the design, based on experience and empirical information. (Srinivasan, 1994)

Tolerancing is a balancing process between multiple factors. While setting tolerances the designer should strive to optimize functionality, manufacturability, interchangeability and costs, this is illustrated in Figure 16. (Syrjälä, 2004)

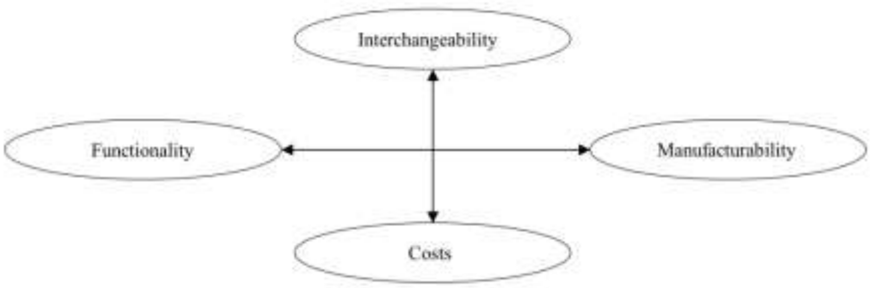


Figure 16. Important factors to be optimized in the tolerancing process. (Syrjälä, 2004)

The use of tolerances are defined in national and international standards: Finnish SFS-standards are compatible and nearly equal to the international ISO-standards. (Syrjälä, 2004)

4.4.1 DIMENSIONAL TOLERANCING

Dimensional tolerances specify part dimension limits to conform to manufacturing variations. Upper and lower limits are specified for the diameter. (Srinivasan, 1994) A unilateral tolerance deviates from the basic size only in one direction while a bilateral tolerance deviates both above and below the basic size. The total tolerance is the difference between the maximum and minimum permissible dimensions. (Mott, 1999)

The term allowance refers to the intentional difference between the maximum material differences between mating parts. The allowance can either be positive, referring to the clearance allowed between parts (clearance fit) or negative (interference fit), resulting in the shaft being bigger than the hole. (Mott, 1999)

The functionality of the assembled parts determines the fit. There are three major types: clearance fit, interference fit and transition fit. Clearance fit indicates that relative motion is permitted between mating parts and assembly can be performed manually. Interference fit does not allow motion, this type of fit is used for permanent assembly that require rigidity and assembly has to be performed by mechanical pressing, heating or shrinking. Transition fit allows marginal clearance or interference. Transition fit is used when accurate location is important, semi-permanent assemblies are accomplished. (Srinivasan, 1994)

4.4.2 GEOMETRICAL TOLERANCING

Dimensional tolerances presume perfect shape of the parts, but in reality it is impossible to produce a part with e.g. perfect circular shape. Geometric tolerances are used to control the allowable variation in form and other geometric attributes and characteristics. There are four main sub-categories in geometric tolerances: (Srinivasan, 1994)

- Form: straightness, circularity, profile, flatness and cylindricity.
- Orientation: perpendicularity, parallelism, angularity.
- Location: position, concentricity, symmetry.
- Runout: total runout, circular runout.

Figure 17 illustrates the difference between a dimensional and a geometrical tolerance.

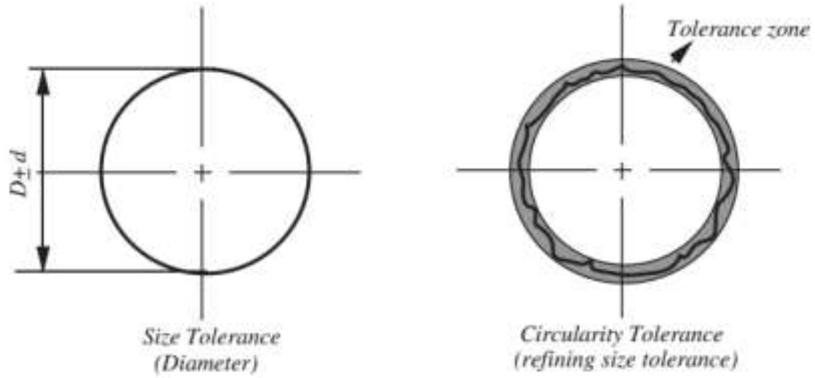


Figure 17. Size (dimension) and circularity (geometrical) tolerances. (Srinivasan, 1994)

4.4.3 GENERAL TOLERANCES

Each feature of a part has to be controlled and therefore toleranced. Dimensions and geometrical features that demand the tightest tolerances are generally individually toleranced. Setting individual tolerances for all features of a part is not practical; therefore general tolerances are used for less critical measures. (Syrjälä, 2004) General dimensional tolerances are introduced in standards ISO 2768-1:1989 and SFS-EN 22768-1. General geometrical tolerances can be found in ISO 2768-2:1989 and SFS-EN 227668-2.

4.4.4 TOLERANCE ACCUMULATION

In assemblies and in parts with multiple features tolerance accumulation causes a problem. The dimensions of the final assembly are directly influenced by the dimensions of mating parts; part tolerances influence critical fits in the design. Tolerances on component parts constitute a tolerance chain. Different types of chains can be identified in a complex assembly; elementary, simple and inter-related. Critical dimensions that exercise maximum influence on the function of the assembly is called a sum dimension. Two models can be used to analyze the tolerance of the sum dimension:

- worst case analysis
- statistical analysis.

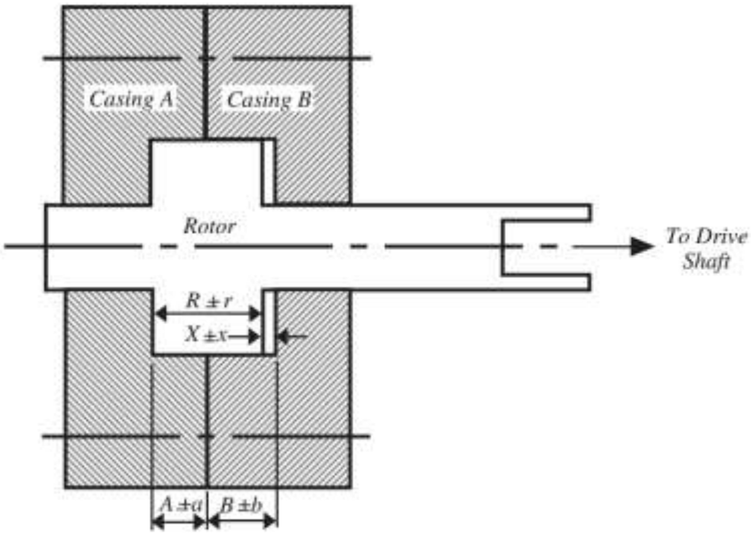


Figure 18. Tolerance Accumulation in gear pump assembly. (Srinivasan, 1994)

Figure 18 displays an example of tolerance accumulation. A cross-section of a gear pump is shown through one of the rotors. The two casings A and B are bolted togheter to form a water-tight enclosure. The clearance X is a sum dimension for the pump to function properly. The rotor width R must be smaller than A+B to ensure rotation. . (Srinivasan, 1994)

In worst case analysis, tolerances are determined by a linear sum of component tolerances, assuming that the real value of each measure is at the tolerance upper or lower limit. In the example shown in Figure 15 the tolerance *x* on the gap is given by: (Srinivasan, 1994)

$$x = a + b + r \qquad (4.1)$$

However, in batch production it is very unlikely that a worst case with maximum upper and lower limit measures would occur. Probability distributions for the tolerances of components produced are used in statistical analysis. The normal distribution of the statistical tolerance can be calculated as the root sum of squares (RSS) as seen below:

$$x = [a^2 + b^2 + r^2]^{\frac{1}{2}} \qquad (4.2)$$

Corresponding techniques can be used to observe the accumulation of tolerances on components during machining, for example tolerance charting which is a semi-graphical method. (Srinivasan, 1994)

4.4.5 TOLERANCES AND DFM

Properly specifying tolerances is one of the most important steps to make designs manufacturable. The use of tight tolerances requires more expensive manufacturing processes, triggering the cost of the product. Unnecessarily tight tolerances should be avoided; designers should understand the fabrication process so they will know the effect of tolerancing and processing. (Anderson, 2008)

The type of process depends on the tolerance; each process has a limit of how tight tolerances can be achieved. If the tolerance is tighter than the limit, the next more precise, and more expensive, process will be used. This is illustrated in Figure 18. (Anderson, 2008)

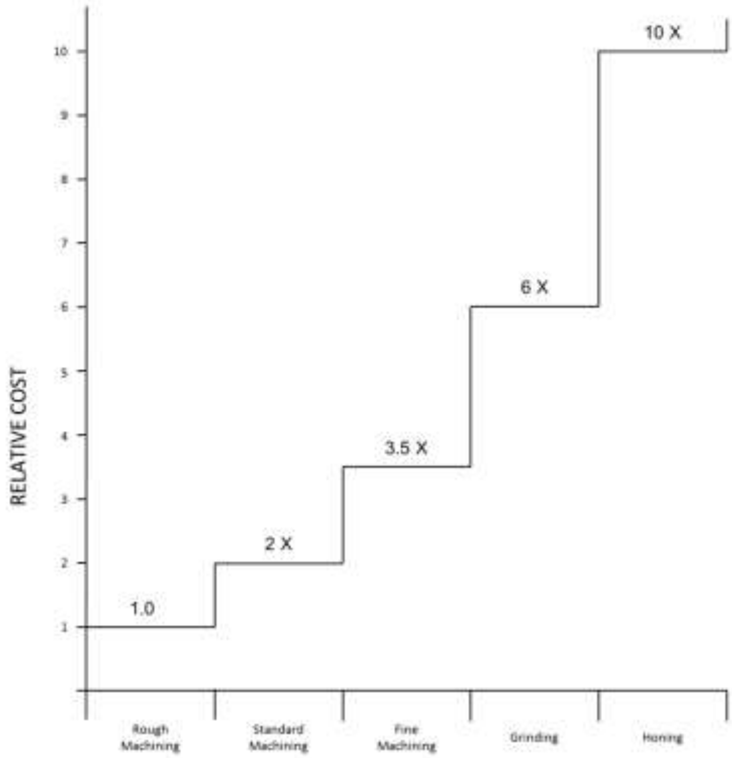


Figure 19. Cost as function of process. (Anderson, 2008)

The cost increase is dramatic when it comes to producing smaller tolerances. Furthermore, producing parts with small tolerances generally require several processing steps. For example a shaft may first have to be turned on a lathe and then ground to produce the final dimensions and surface finish. Each subsequent step in the manufacture adds cost. Also even if different processes are not necessary, achieving small tolerances on a single machine may require several passes causing cost to rise. (Mott, 1999)

On the other hand, if tolerances are specified or interpreted too loose, the product may lack functionality, encounter assembly difficulties, have quality problems, wear out prematurely and even cause safety hazard. (Anderson, 2008)

4.4.6 TOLERANCES AND QUALITY

The industrial practices of Japan have been revolutionized by Taguchi's method of quality engineering. Taguchi's method includes tolerance design, system design and parameter design. An important concept in Taguchi's philosophy is that a loss to the manufacturing company and, and are called *quality loss* or *loss to society*. (Srinivasan, 1994)

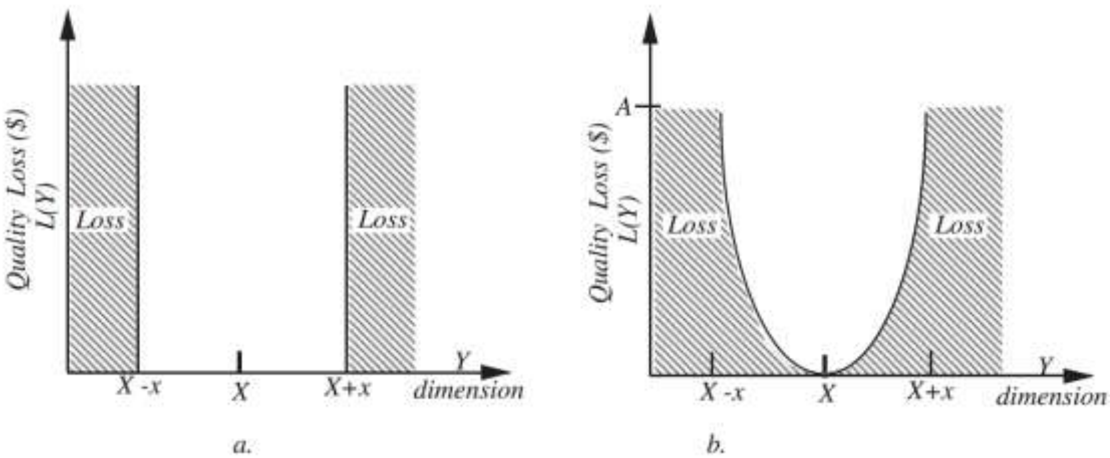


Figure 20. Interpretation of Quality and Tolerances according to a. Conventional b. Taguchi. (Srinivasan, 1994)

In the conventional interpretation parts with dimensions that do not conform to the tolerance specifications ($X \pm x$) are either reworked or scrapped, causing a "loss" to the manufacturer, while the parts with dimension within tolerance limits are presumed as equally good according to Figure 20 a. However, parts with dimensions closer to the tolerance limits tend to perform poorly in comparison to parts with dimensions closer to the nominal. The poor performance results in quality loss. Taguchi proposes a graduation in the quality loss shown in Figure 20 b. A possible representation of this loss is a "quadratic loss function" expressed below:

$$L(Y) = K(Y - X)^2 \tag{4.3}$$

where *L(Y)* is the loss for a dimension *Y*, and *K* is a constant estimates from a knowledge of the loss due to scrapping a part according to $K=A/x^2$ where *A* represents the loss and *x* the tolerance. The loss function can be used to acquire new values for altered tolerance limits, taking into consideration economic factors like the cost to repair a part. (Srinivasan, 1994)

Taguchi's method of continuous quality loss provides a tool to unify apparently unrelated issues in design engineering as manufacturing, performance, quality and cost. The concept can be used for a number of engineering quantities and not only mechanical dimensions. Unfortunately Taguchi's tolerance design methods have not been extended to geometric tolerances, presumably since the lack of parameters to quantify from ideal geometric form. (Srinivasan, 1994)

4.4.7 OFFSET SOLIDS THEORY

The representation of tolerances in geometric 3D modeling systems is a challenging problem. Requicha is proposing an alternative and mathematically rigorous interpretation of size tolerances, exploring an extension to include geometric tolerances. The offset solids theory is presented as an alternative method for representing tolerance zones. The method uses Minkowski operators, dilation and erosion. A disk of diameter equal to the width of the tolerance zone is swept over the line, with the center of the disk below the line, an expanded line version is created as shown in Figure 21. This is called Minkowski addition or dilation. Sweeping the disk over the line with the center above it, creates a contracted version of the line. This operation is Minkowski decomposition, or erosion. The tolerance zone is constructed by subtracting the contracted version from the expanded one. These procedures can be expanded to complex shapes and mapped into data structures enabling representation of mechanical components in computer models. (Srinivasan, 1994)

Figure 21. Geometric tolerancing by offset zones.

DESIGN PART

5 INTRODUCTION

5.1 PROJECT DEFINITION

The primary aim of the productization project is to develop a motor for series production from a prototype motor. Facing high production volumes production cost and product quality assurance becomes of big importance. The production cost of the productized motor should be reduced with 90% in comparison to the prototype motor and production batch should be 500 motors per year. Design methodology design for manufacturing is used.

5.2 HIGH-SPEED INDUCTION PROTOTYPE MOTOR

An exploded figure of the high-speed induction motor can be seen in Figure 22 and design specifications for the prototype motor are shown in Table 1. The prototype motor is a 3-phase high-speed induction motor with a copper coated massive rotor. The motor is horizontally foot mounted according to IM 1001 with one external shaft extension. The motor is protected by enclosure IP 23, which implies that the motor is protected against solid objects greater than 12mm and spraying water. Method of cooling is IC 25/ 35, insulation class F. Rotational speed of the motor is 21000 rpm and rated output 86kW. Frame size is 160, implying 160mm distance from shaft to ground.

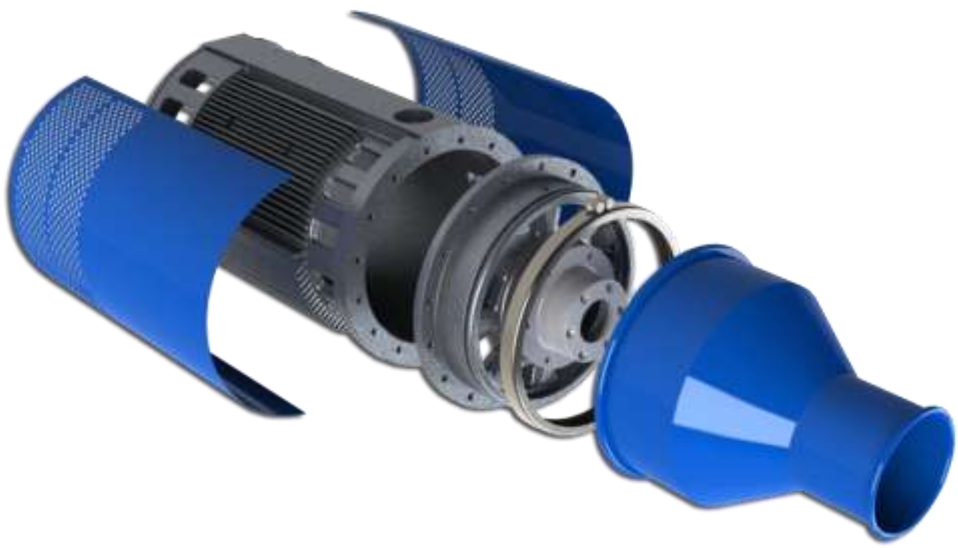


Figure 22. Explosion figure of the prototype motor.

Table 1. Design specifications for the solid-rotor induction prototype motor.

Motor type		High-speed induction motor with copper coated solid rotor		
Mounting designation		IM 1001		
Protected by enclosure		IP 23		
Method of cooling		IC 25 / 35		
Insulation		Class F		
Ambient temperature, max.		40 °C		
Altitude, max.		1000 m.a.s.l.		
Duty type		S9		
Temp. rise		Class B		
Connection of stator winding		Star (internal)		
Rated output		86 kW		
Voltage		380 V ± 5 %		
Frequency		354 Hz		
Speed		21000r/min		
Current		220 A		
No load current		135 A		
Rated torque		39 Nm		
Load characteristics	**Load %**	Current A	Efficiency %	Power Factor
	100	220	95.9	0.63
	75	188	96.0	0.56
	50	163	95.5	0.43
Estimated losses (100% Load)				
Friction		700 W		
Stator		1700 W		
Rotor		1300 W		
Total		3700 W		

The rotor concept in the motor is a solid rotor with copper coating. Advantages with the rotor concept are easy construction, robust, consistent quality and high stiffness. The production method of the prototype rotor is first creating a copper lamination by explosion welding on the rotor and thereafter machining to achieve final geometry. Stiffness is improved by the explosion welding; the strength of the copper is doubled during explosion welding. A 3D cross section drawing of the motor displaying machine inner structure and also the machine cooling topology is shown in Figure 23. The motor is totally air cooled with suction from the N-end through the end shield.

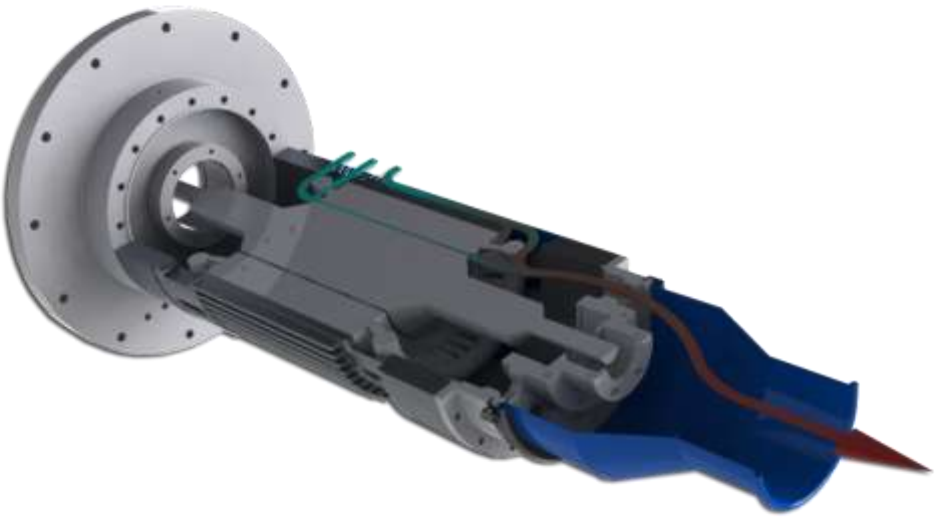


Figure 23. Prototype motor cross section and cooling topology.

5.3 COST ESTIMATION

To determine the substantial goals a cost breakdown analysis of the prototype motor was made. Material cost breakdown analysis of motors with similar size and output power was made to be able to compare with a material cost breakdown of the prototype motor for an estimation of the differences in manufacturing costs.

5.3.1 PROTOTYPE MOTOR

Figure 24 shows a cost breakdown structure for the most relevant parts of the prototype motor.

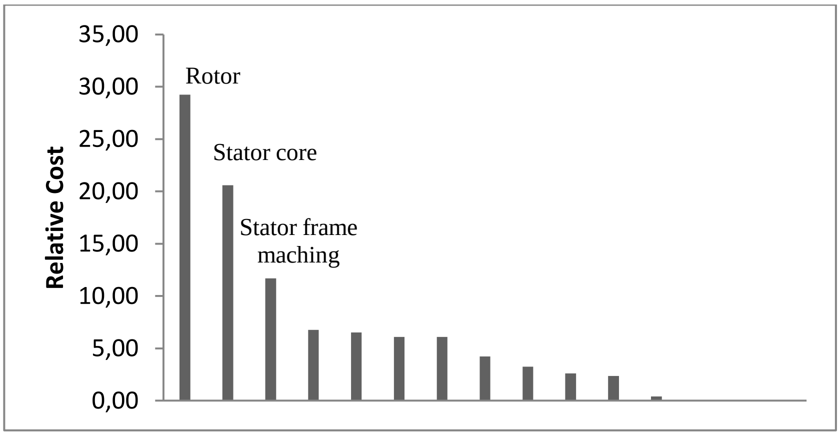


Figure 24. Cost breakdown structure for the prototype motor.

The most expensive part of the prototype motor is the rotor. Normally the most expensive part of a motor is the stator. This indicates cost reduction possibilities by means of finding more inexpensive means to fabricate the rotor. Figure 24 also indicates that the cost of other parts such as end shields and bearing covers should be reduced.

Figure 25 depicts a cost breakdown structure for materials used for the prototype motor.

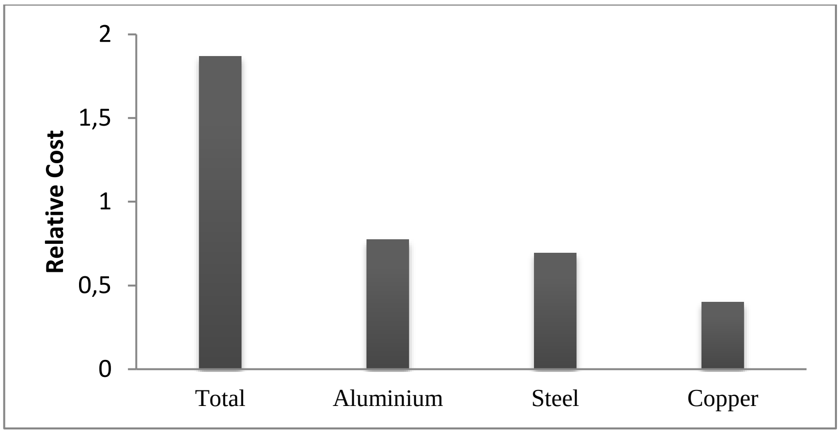


Figure 25. Cost breakdown structure for materials used for prototype motor

According to Figure 25 the total materials cost for the prototype motor is only 2% of the total cost. This indicates that tooling and processing costs are major part of the motor production costs, and there is room for cost reduction in matter of reducing processing costs.

5.3.2 STANDARD MOTOR

A material cost breakdown structure for a standard motor of frame size 132 is illustrated in Figure 26. This motor has about the same physical size as the prototype motor and output power 5.5 kW.

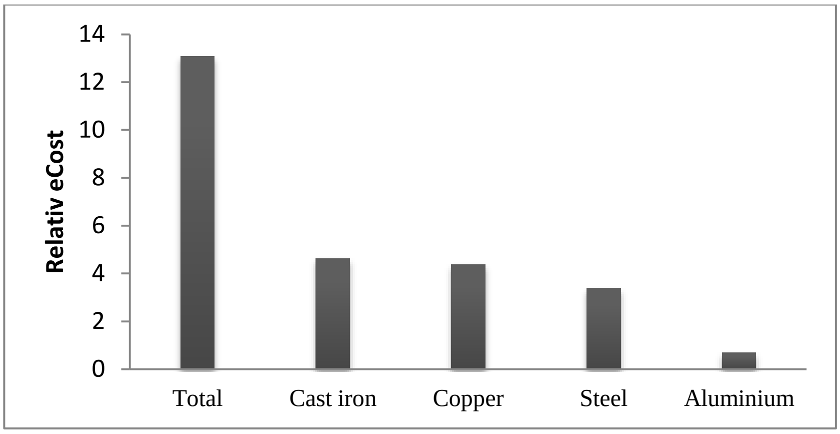


Figure 26. Cost breakdown structure for materials used motor of similar size.

Figure 26 illustrates that total material cost for the motor is around 13 % of the production price in comparison to 2 % of the prototype motor.

A cost breakdown structure for a motor of frame size 280 is illustrated in Figure 27. This motor has a similar output power value as the prototype motor. The output value of the catalogue motor is 90 kW, while the output value for the prototype motor is 86 kW.

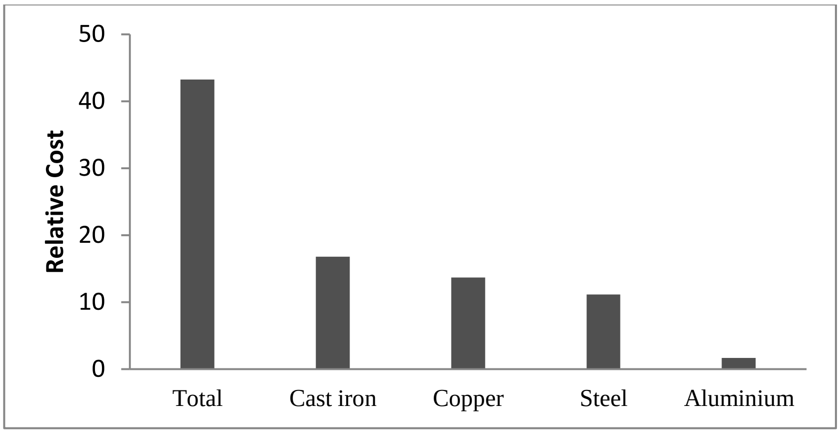


Figure 27. Cost breakdown structure for materials used for motor with similar output value.

According to Figure 27 the total material cost for the motor is around 43 % of the production price. This is due to the fact that the latter motor is ten times heavier; material costs increase more rapidly with size then machining costs.

6 ROTOR

6.1 PROTYPE ROTOR

The prototype rotor is the most challenging part to produce. The prototype rotor is copper coated by explosion welding as shown in Figure 28. Explosion welding causes the rotor not to be entirely straight; during the explosion welding process bending of the rotor occurs and before end processing the rotor needs to be straightened by machining. This causes the copper layer to have non-uniform thickness after straightening. A non-uniform copper layer causes non-uniform thermal expansion of the copper during operation of the machine, which in turn causes uneven force distribution in the rotor.

Explosion welding also induce stresses in the rotor. These stresses release after a while and cause small deformations of the rotor, meaning the measures of a rotor where the stresses have been released may not be in line with geometrical tolerances.

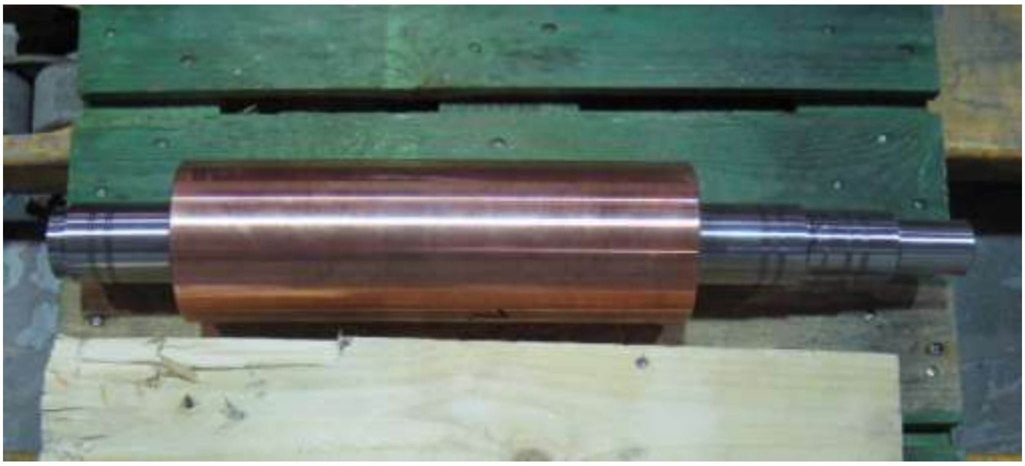


Figure 28. Prototype rotor copper coated by explosion welding.

Using another method for copper layering would reduce the machining cost by 50%. Currently machining of the rotor takes a week and two machinists are needed since the machinist performing the straightening of the rotor needs to instruct the machinist performing the end processing. If there would be no need for rotor straightening the rotor could be put directly into a CNC lathe.

Tolerances of the prototype rotor are also problematic due the fact that they are in a scale of micrometers (µm). These kind of tolerances require precision grinding, also the error of measurement of the measurement equipment is ±3µm, meaning tolerances in this scale is very hard to achieve. Figure 29 displays the most important measures of the prototype motor shaft, and the tolerances that are challenging.

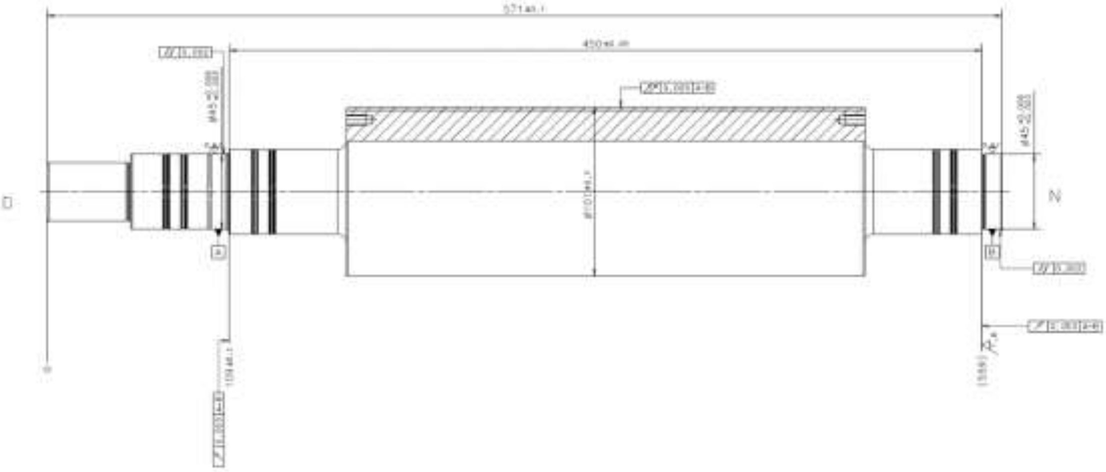


Figure 29. Prototype motor rotor drawing displaying main dimensions and toleranced dimensions of significance.

The need for precise bearing alignment in high-speed motors creates a need for tight geometrical tolerances. The dimensional tolerances on the bearing fits also cause a cost rise, but they might be loosened to normal tolerance values, while the geometrical tolerances are indispensable. Figure 30 depicts that the dimensional tolerances for the bearing fit could be loosened to the tolerance grade IT5.

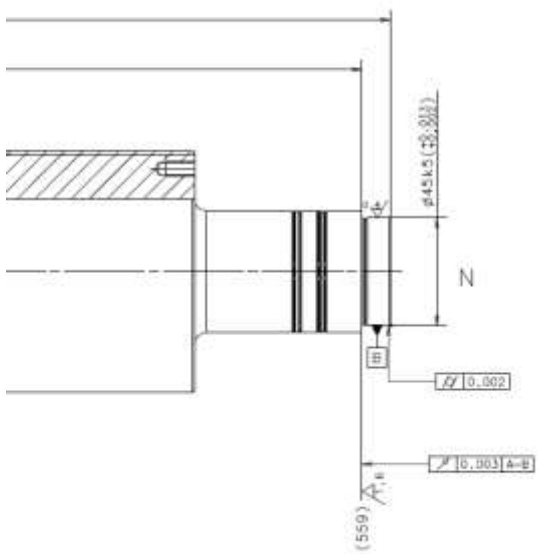


Figure 30. N-end of shaft, the bearing fit tolerances are subject for altering but not the geometrical tolerances.

6.2 ROTOR CONCEPTS

Since the copper coated rotor is troublesome to produce by explosion welding, other motor and rotor types as well as methods of improving electrical properties are explored. The methods for improving electrical properties can be used solely or several of them can be used. For example a solid rotor can be produced with copper coating and slits, alternatively squirrel cage and an end ring structure. An objectives tree is presented in Figure 31 showing the different alternatives.

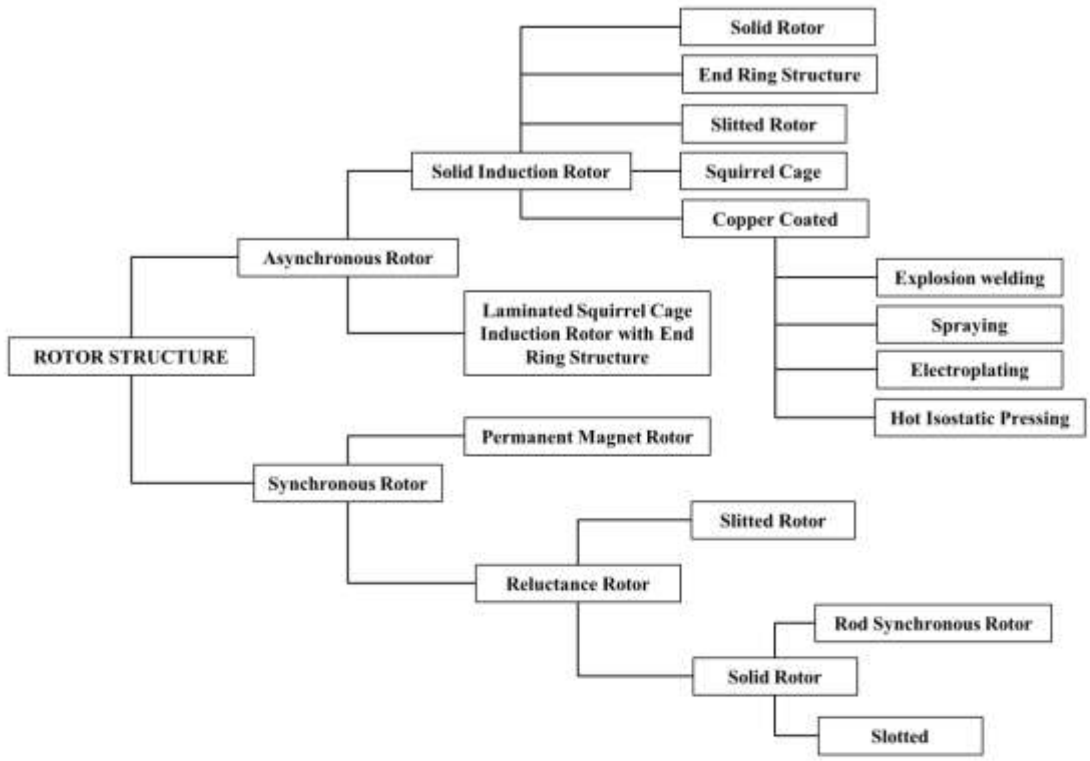


Figure 31. The objectives tree for design of rotor structure.

An induction rotor alternatively a synchronous rotor could be used for the high-speed motor. The induction rotor type was chosen for the prototype motor since a synchronous rotor is more complicated to produce. Laminated squirrel cage rotors are used in high-speed motors whenever possible. The rotational speed of the high-speed motor implies that it is in the border zone for choosing between a standard laminated squirrel cage rotor and some type of solid rotor. A copper coated solid rotor was chosen for the prototype since the tooling for producing a laminated rotor was not available and obtaining tooling would lead to too high fixed costs for prototype making. For serial production, however, a laminated rotor should be considered since they provide several benefits over solid rotors when it comes to lowering cost and electrical properties.

Figure 33 and Figure 32 displays the different process stages for the rotor alternatives and a comparison between the numbers of process stages.

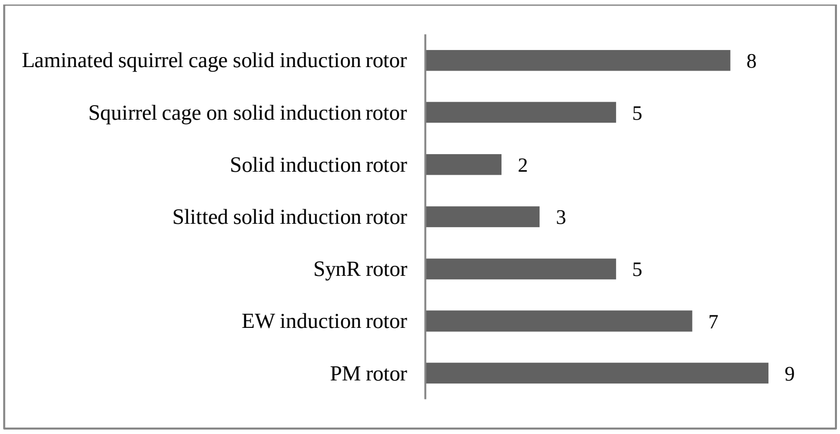


Figure 32. Number of process stages for the different rotor alternatives.

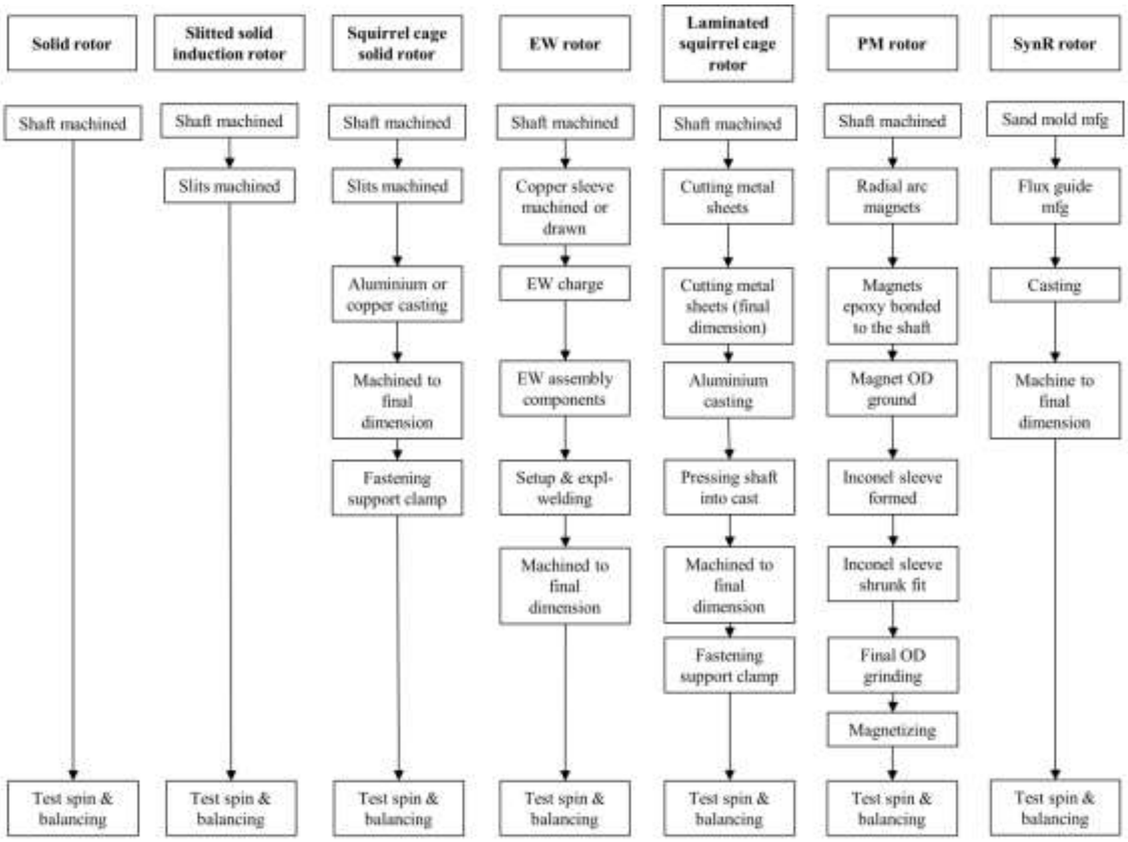


Figure 33. Process stages for the different rotor alternatives.

Comparing the different rotor alternatives it can be assumed that more process stages makes rotor production less feasible. This is not true in the case of laminated rotors, since they are normally easy and cheap to manufacture, with standard production processes.

A pro/con chart for the different rotor alternatives is displayed in Table 2.

Table 2. Pro/Con chart for different rotor types.

	Laminated Squirrel Cage Rotor with End Ring Structure	**Solid Rotor**	**Copper Coating by EW**	**Slitting**	**Squirrel Cage Solid Rotor**	**End Ring Structure**
Pro	Best electrical properties, usually cheap to fabricate	Very good mechanical properties, easy and cheap to produce	Stable, good mechanical and electrical properties, familiar technology	Good electical properties	Good electrical properties	Good electrical properties
Con	Requires expensive equipment purchase, special end ring structure set up needed due to greater centrifugal forces.	Poor electrical properties.	Expensive to produce, varying test results from prototype testing with explosion welding, other methods not tested.	Not tested, technology not familiar, might induce high friction loss	Expensive to produce, some rigidity of the solid rotor might be lost	Suitable productio n method not known

The laminated squirrel cage rotor with and end ring structure has the best electrical properties and fabrication is cheap if necessary production equipment is available. In turn to produce a laminated squirrel cage rotor for the rotor size in question production a rotor sheet cutting machine and a cast mould needs to be purchased. For this reason laminated rotor prototypes have not been possible to produce; the fixed costs for producing laminated rotors are so high, but a laminated rotor might be an alternative in the productization stage. A laminated induction rotor for a conventional induction motor is displayed in Figure 34

Figure 34. Laminated squirrel cage rotor.

Producing a laminated squirrel cage rotor for a high-speed motor would require fastening support clamps at the end rings for sufficient mechanical rigidity. Fastening support clamps also adds an extra process stage.

Laminated rotors do not provide the same stiffness as solid rotors and the critical frequency of a laminated rotor is quite low; around 8 krpm. This indicates that the motor would have to operate above the first critical speed of the rotor. Another disadvantage with laminated rotors used in high-speed system is the fact that balancing of rotors is troublesome. Each rotor would have to be operated during a longer time span during the test spin and balancing stage.

The solid rotor is cheap and easy to produce, while the efficiency and electrical properties are poor. Solid rotors have significant heat loss and provide only half the power compared to a coated rotor. The temperature rise of a solid rotor is so significant that a solid rotor would be impossible to utilize in a high-speed motor. Loading of a solid rotor is not even possible due to the temperature rise. Figure 35 displays a solid rotor.

Figure 35. Solid rotor.

Copper coating of the rotor results in good electrical properties. However, problems observed during prototyping indicate that the copper coating is not very stable; there is a problem with balancing and the final copper coating layer is non-uniform causing uneven heat expansion of the rotor copper layer. Testing has shown that copper coating has sometimes been successful and sometimes not, the origin of the problem might be that the prototype copper coated rotors were produced using handwork and not an automated process. Figure 36 displays a copper coated solid rotor.

Figure 36. Copper coated solid rotor.

Copper coating can be done by explosion welding, hot isostatic pressing (HIP), spraying or electric plating. The advantages with explosion welding and hot isotatic pressing is a thicker copper layer that would conduct electricity as well as not let high-frequency harmonics penetrate, while the other two alternatives can only provide a thin layer. A thinner layer would not function as a good electrical conductor. The HIP method functions in theory and is a good method for mass production; however the method has not been tested for copper coating rotors. An alternative would be coating the rotors by spraying or electrical plating and then slitting them to maximize the electrical properties.

Table 3. Pro/Con chart for different copper coating methods.

Copper coating method	**Explosion welding**	**Hot Isostatic Pressing**	**Spraying**	**Electrical plating**
Pro	Possible to make copper coating thick enough to conduct electricity and not let the high-frequency harmonics penetrate.	Suitable serial production method. Possible to make copper coating thick enough to conduct electricity and not let the high-frequency harmonics penetrate.	Possible to make copper coating thick enough to not let the high-frequency harmonics penetrate.	Possible to make copper coating thick enough to not let the high-frequency harmonics penetrate.
Con	Expensive production method, problems occured during testing, they might however resolve if the process is automated	Not tested	Copper coating will not be thick enough to conduct electricity.	Copper coating will not be thick enough to conduct electricity.

The main advantage with the copper coated explosion welded rotor is the fact that production technology is known and the method is tested.

Slitting the rotor is an inexpensive production method. Figure 37 displays a slitted solid rotor.

Figure 37. Slitted solid rotor.

A slitted rotor would be a good alternative for the high-speed motor even in serial production due to the short and simple production process. The rotor slits induce an increased amount of cooling but also higher friction loss. According to test results slitted rotors induce substantial temperature rise in comparison to copper coated rotors. Roughly the temperature rise of a slitted rotor is 181% higher than the temperature rise of a copper coated rotor. Whilst the temperature rise of the copper coated rotor is 49 K the temperature rise of the slitted rotor is 138 K. The main problem with the temperature rise of the slitted rotor is the fact that the maximum operating temperature of the hybrid bearings used in the prototype motor is only 100˚C. However, the inexpensiveness of producing the slitted rotor might outweigh the disadvantages. Utilizing another bearing type that could withstand the temperature induced by the slitted rotor might be the most viable option. Another option would be trying to improve the electrical properties of the slitted rotor by putting a thin layer of copper coating on it.

An end ring structure would provide good electrical properties, but production methods are not known and further product development would have to be conducted to evaluate this rotor concept. Also if end rings would be used, some kind of support clamp would have to be used to support the end rings against the centrifugal forces and the end ring material would have to be carefully chosen due to the thermal requirements.

7 BEARING ARRANGEMENT

The bearing system is illustrated in the cross section assembly drawing in Figure 38. The locating bearing is located in the shaft drive end and the non-locating bearing is located in the non-drive end. The non-drive end has a preload to support the non-locating bearing and the outer bearing cover is sealed.

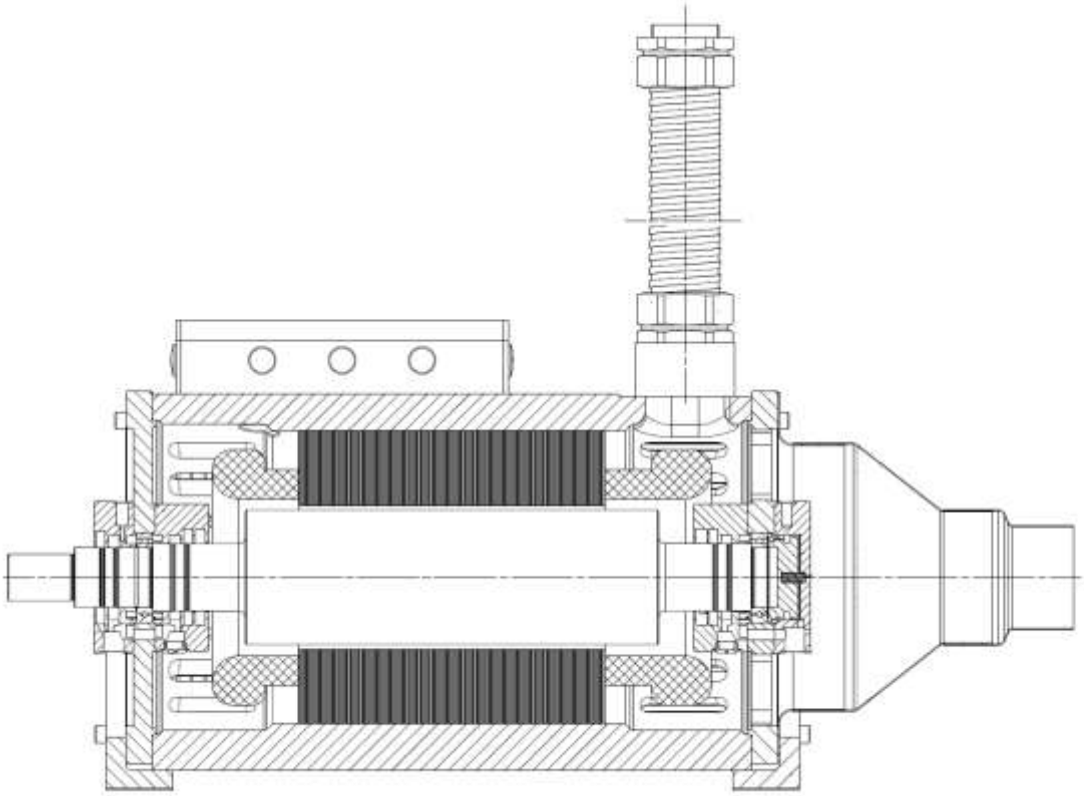


Figure 38. Assembly drawing of prototype motor.

7.1.1 BEARING TYPE USED

Bearing type used in the prototype motor is a hybrid spindle bearing of the type single row angular contact ball bearing. The bearing is a super precision sealed bearing with small ceramic balls. The bearing arrangement is individual, and light preload is required. Angular contact ball bearings have raceways in the inner and outer rings that are displaced in the direction of the bearing axis, implying the bearing can accommodate combined loads; axial and radial loads simultaneously. The bearings are oil lubricated with forced circulation lubrication. An image of the bearing used in the motor is shown in Figure 39.

Figure 39. Hybrid bearing type used in prototype motor.

A disadvantage with the hybrid bearing is the fact that it can only stand temperatures up to 100˚C. This regulates the possible temperature rise of the motor, which in turn regulates the rotor concept used. More efficient cooling could be utilized to cool down the bearings but this might not be feasible regarding the production costs. Fan cooling might not be powerful enough and water cooling would increase system complexity.

Magnet bearings and gas bearings would be feasible options since there is no friction in these bearing types and they withstand high temperatures. Currently magnet bearings are very expensive and utilizing gas bearings require customized design. Utilizing gas bearings would be possible in serial production but this would only be reasonable if there is much certainness that the product is profitable. Another reason for not utilizing gas bearings is the fact that many high-speed applications require axial loading and gas bearings do not withstand loading in the axial direction. Magnet bearings however do. Utilizing magnet bearings would be the best option if it wasn't for their expensiveness.

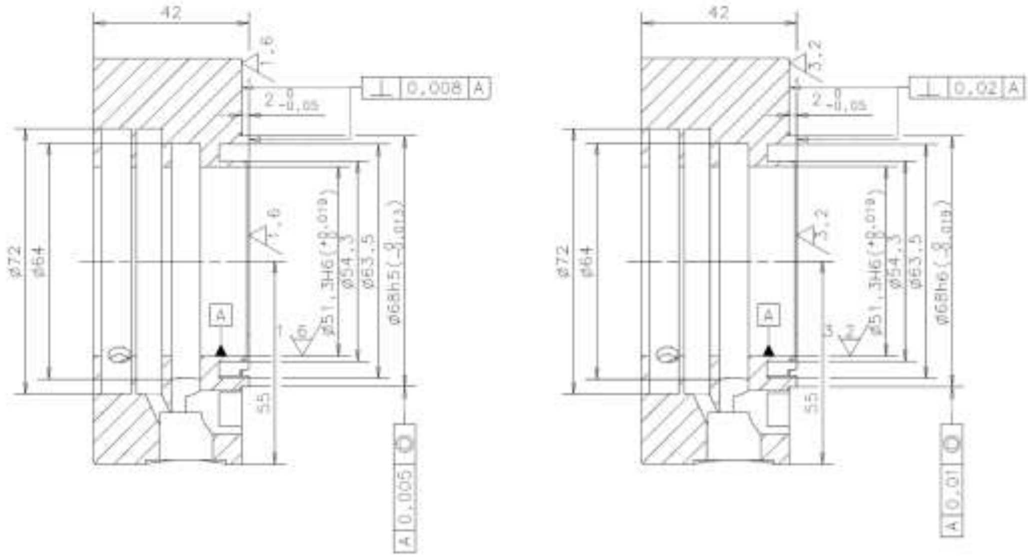
The most feasible alternative at the moment would probably be using a bearing with a plastic clamp. The plastic has ¼ of the yield strength compared to steel but since the plastic material is lighter the centrifugal forces induced are smaller and cause less heat generation.

7.1.2 INNER BEARING COVERS

The inner bearing covers are shown in Figure 40. The function of the inner bearing covers are supporting the bearing from the side, sealing the bearings and working as a channel for the lubrication.

Figure 40. Inner bearing covers.

The prototype motor inner bearing covers have very tight tolerances and the lubrication channels for the inner bearing covers are also hard to machine. A measurement drawing displaying main and toleranced dimensions of significance for the inner bearing cover can be seen in Figure 41. The geometrical tolerances are in micrometers (µm) and measuring exactness of the measures is troublesome. Furthermore small tolerances on shaft shoulder structures are also harder to achieve, than e.g. tight tolerances in holes. The bearing cover has a h5 tolerance on a small shoulder structure. Surface quality is set to 1,6 for some specific surfaces, this might not be completely necessary and setting a surface quality of 3,2 might lower costs. The geometrical tolerances were loosened to tens of micrometers and the h5 tolerance was set to h6. A prototype was made to determine cost reduction and function of the part.



a. b.

Figure 41. Measurement drawing for prototype motor inner bearing covers with a. original tolerances and b. altered tolerances.

The prototype bearing support parts are machined from steel type S355. A more suitable material for the bearing covers would be quenched and tempered steel, this steel type has greater toughness and strength than non-tempering steel. By using tempering steel achieving tolerances and machining also becomes easier.

7.1.3 OUTER BEARING COVERS

The outer bearing covers are designed differently depending on location. The non-drive outer bearing cover is sealed and preloaded to support the non-locating bearing. The outer bearing cover for the non-drive end is shown in Figure 42 and for the drive end is shown in Figure 43.

Figure 42. Outer bearing cover for non-drive end.

Figure 43. Outer bearing cover for drive end.

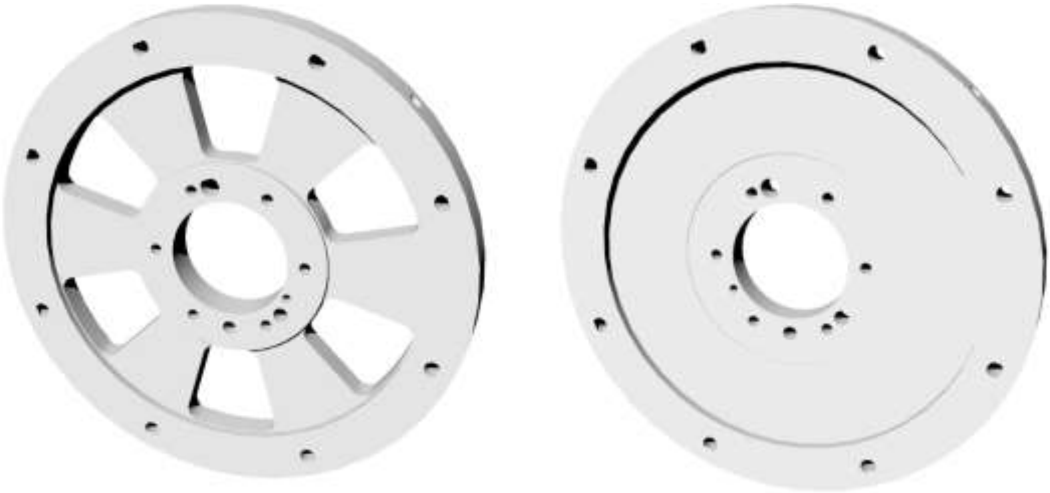
The tolerance and machining problems for the outer bearing covers are roughly the same as for the inner bearing covers; tight geometrical tolerances, tight tolerances on small shaft shoulder structures and lubrication channels pose a challenge.

There is a clearance fit at the non-locating bearing in order to support movement of one bearing ring in relation to the other. The term *bearing clearance* implies the radial or axial distance the parts can move in relation to each other without loading. This is necessary since the thermal expansion of the bearing is bigger than the thermal expansion of the support parts.

The N-end bearing cover has a preload to support the non-locating bearing. The preloaded structure is obtained by using a spring and an O-ring. However, the preload design on the non-drive outer bearing cover is a subject of redesign since the functionality failed during prototype testing.

8 END SHIELDS

The function of the bearing end shields is closing the motor from the side and giving support to the bearings in radial direction. The prototype motor bearing end shields are made of S355 steel. The end shields can be seen in Figure 44. The non-drive end shield has openings for the cooling air flow; the cooling air pump is mounted to the non-drive end. The bearing end shield design for the drive end is basically the same as for the non-drive end, except for the cooling flow openings.



a. b.

Figure 44. Prototype end shields for a. non-drive and b. drive end.

In serial production the end shields would be made of cast iron. End shields and stator frame feet are separate parts in the prototype motor, due to easiness of machining when using steel parts. An assembled prototype motor is displayed in Figure 45.

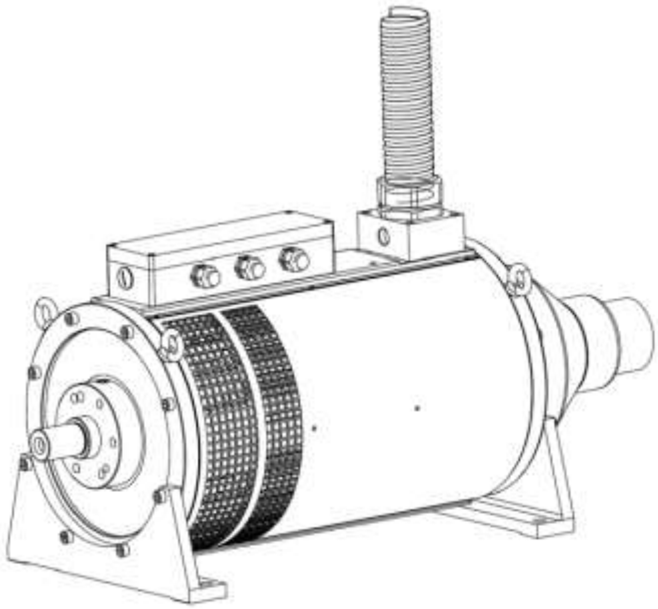


Figure 45. Assembled prototype motor.

However, in serial production it would be more profitable to invest in a cast mold combining the bearing end shields and the stator feet in the same part. The openings for the cooling air should also be incorporated in the cast mold to reduce the amount of machining of the part. The bearing end shields and stator frame feet could be easily incorporated in a cast mold as shown in Figure 46.

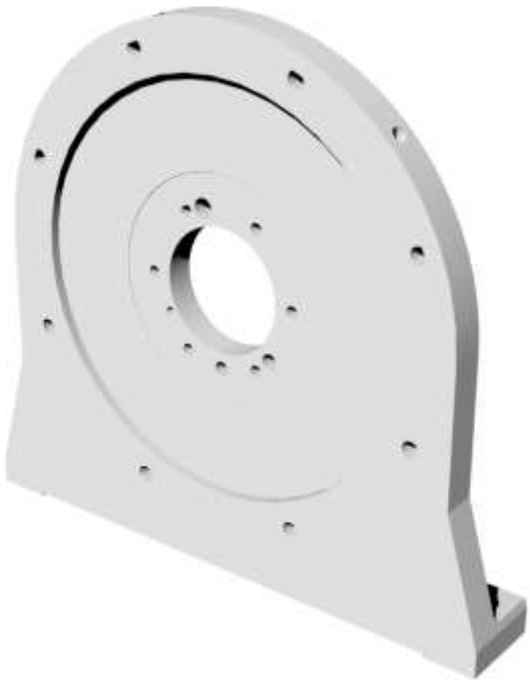
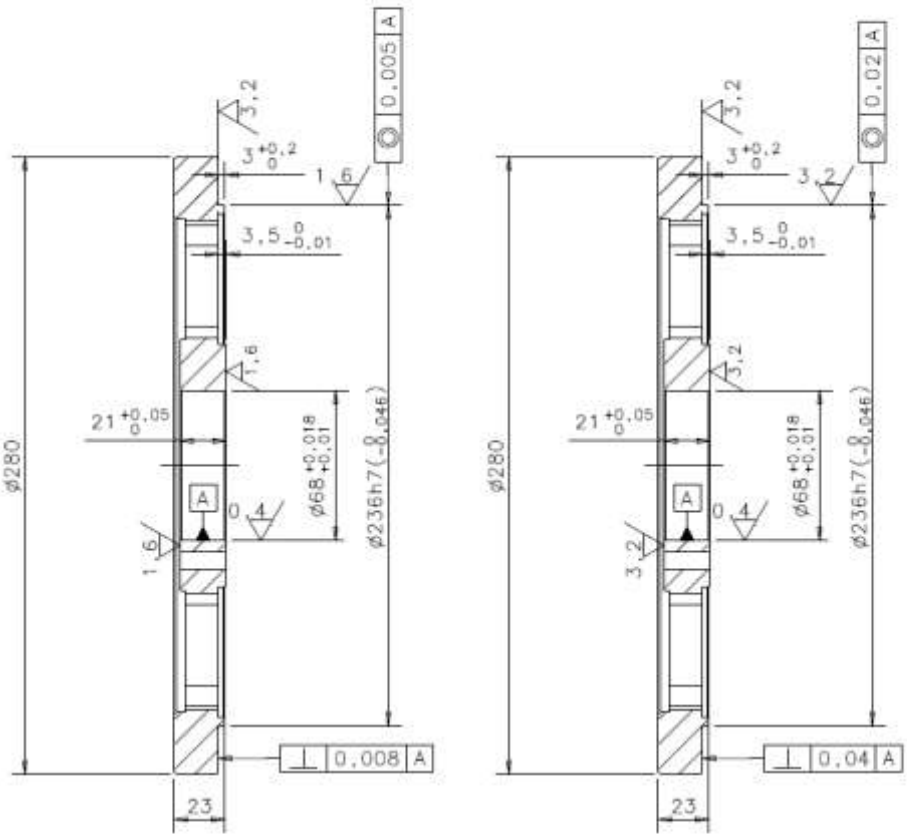


Figure 46. Drive end shield and motor feet incorporated.

The tolerances for the motor end shields are significant for bearing alignment. Tolerance accumulation occurs, since the end shields are attached to the stator frame. The tolerances of the prototype motor end shields are therefore tight. A measurement drawing for the prototype motor non-drive end shield is shown in Figure 47. The measurement drawing only displays main dimensions and toleranced dimensions of significance. The geometrical tolerances are in micrometers, the size of a unilateral tolerance is only 8 µm and there is also a very fine surface quality of 0,4 µm. The geometrical and surface tolerances are subject for loosening, but the dimensional tolerances are necessary to ensure proper motor operation. Some tolerances are specified by the bearing supplier, these might have to be loosened to improve producibility.



a. b.

Figure 47. Measurement drawing for a. prototype motor bearing end shields b. end shields with altered tolerances.

9 STATOR

The prototype motor stator sheets are produced by laser cutting and are therefore costly; in serial production the cost of producing the stator sheets will be lowered with 95%. Serial production justifies higher fixed costs and tailored production equipment, therefore overall costs will be lowered. The stator sheets of the prototype motor are shown in Figure 48.

Figure 48. Stator sheets of the prototype motor.

9.1 STATOR FRAME

The production method of the prototype stator frame is aluminum casting. Problematic with the casting is alignment problems. Unevenness in the cast was another problem as shown in Figure 49. An alternative serial production method would be using aluminum extruded shapes with holes to be machined.

Figure 49. Stator frame for prototype motor.

However, the aluminum cast stator frame was made since it was assumed that the motor needs smaller cooling ribs for increased air flow on the outside. Testing show that this is not the case and in serial production the stator frame can be made of cast iron with standard production methods.

10 DISCUSSION

10.1 SUMMARY OF RESULTS

A cost breakdown analysis for the different motor parts and materials used was made to determine what factors were pushing the price up in the high-speed motor compared to a standard motor. The cost estimation showed that the most expensive part of the prototype motor is the rotor, whilst in a standard motor it is the stator. The cost breakdown also depicted that the material costs of the prototype motor is only 2% of the total cost, indicating that the parts processing costs are the major cost drivers in the prototype motor.

The copper coated solid rotor is the most challenging part to produce in the prototype motor. If another copper coating method would be used the cost could be reduced with 50%. Using explosion welding it has also not been possible to get a uniform copper layer, due to bending of the rotor during the welding process. Another problem with explosion welding is tension releasing afterwards causing the rotor dimensions to change. The rotor bearing tolerances were loosened to tolerance grade IT5, the original range was 3µm and the measurement error of the measurement equipment is ±3µm, this makes the prototype rotor almost impossible to produce.

Different rotor concepts were evaluated. It was decided that an induction rotor should be chosen since they are simpler to produce than a synchronous rotor. Laminated squirrel cage rotors are used in high-speed motors whenever possible. This high-speed motor lies in the border zone for choosing a laminated or solid rotor. A solid rotor is more optimal for prototype making since the fixed costs for producing a laminated squirrel cage rotor are high.

Comparing the number of process stages shows that the permanent magnet rotor has the highest number of production stages followed by the laminated squirrel cage rotor. Normally it is more feasible to produce a rotor with less production stages however, this is not true in the case of laminated squirrel cage rotor since this rotor type is normally easy and cheap to produce. The rotor with the least number of process stages is the solid rotor, but the solid rotor also has the least satisfying electrical properties.

All rotors have either advantages like good electrical properties (laminated squirrel cage) or good mechanical properties (solid rotor), or a combination of both. However, laminated squirrel cage rotor production requires expensive equipment purchase and a special end ring structure, while the solid rotor as mentioned has poor electrical properties. Disadvantages with the other rotors are connected to the fact that the rotors would need more testing or that a suitable production method is undeveloped.

To use a laminated squirrel cage rotor for high-speed support clamps would need to be fastened at the end rings for mechanical rigidity and this support method is not known yet. The motor also would have to operate above first critical speed of the rotor. Balancing the rotors would also be more troublesome than in normal speed applications.

The temperature rise of the solid rotor is so significant that it would be impossible to utilize a solid rotor in a high-speed motor. Copper coating increases the electrical properties. The copper layer however, is usually non-uniform causing non-uniform heat expansion of the rotor due to the variation in metal composition. There is also a problem with balancing. Sometimes copper coating has been successful and sometimes not. The reason for the quality variation might be the fact that the explosion welded rotors have been produced by handwork and not an automated process. Other methods for copper coating than explosion welding are available, but they either produce a thinner copper layer than necessary to conduct enough electricity or the methods have not been tested enough.

Slitting a solid rotor also increases the electrical properties, manufacturing slits is cost efficient and easy. Although, the problem with the temperature increase also applies to slitted rotors. The temperature rise of a slitted rotor is 138 K and the bearing type used in the high-speed prototype motor can only withstand 100 ºC. An option would be to utilize a bearing type that can withstand higher temperatures alternatively putting a thin copper layer on the slitted rotor.

The bearing used in the high-speed prototype motor is a super precision sealed hybrid bearing. The fact that this bearing type withstands only 100 ºC regulates the rotor concept. A new cooling system design would increase system complexity and fan cooling is not efficient enough for excessive cooling. No-friction bearings like gas or magnet bearings would be feasible options if magnet bearings would not be too expensive and gas bearings would take axial loading. The most feasible option would be using a less dense bearing with a plastic clamp that would cause less heat generation.

The bearing support part tolerances were loosened in some places. The geometrical tolerances, originally in micrometers were loosened to tens of micrometers. The bearing covers had a h5 tolerance at a small shoulder structure, which is hard to achieve, the tolerance was loosened to h6. Minimum surface quality was set from 1,6 to 3,2. Quenched tempered steel could be used instead of S355 since this steel type has greater toughness and is easier to machine. The end shields were integrated with the stator frame feet.

The cost of producing the stator sheets will be reduced with 95% in serial production, using standard serial production equipment instead of laser cutting. According to testing of the high-speed prototype motor a standard cast iron stator frame can be used, since extra cooling ribs are not necessary, this also reduces the production cost.

10.2 DISCUSSION

The aim of the productization project was to develop a motor for series production from a high-speed prototype motor reducing the production costs of the motor with 90% for a batch of 500 motors per year. The project turned out more complex and the final result is more a conduct of research to see if there is a possibility to develop a high-speed motor for serial production.

The main research problem was constructing a profitable product from a view of manufacturing technology also satisfying quality demands. Most motor parts have been redesigned by principles of DFM as integrating parts and using loosest possible tolerances. The aim while altering the tolerances was to keep functionality and quality assurance of the bearing system, the recommendations from the bearing suppliers however have not been followed in some cases. The bearing suppliers set the tolerances tight to ensure bearing functionality with broad margin and in reality the tolerances can be loosened.

The most problematic with the whole project is finding a rotor – bearing combination that satisfies both electrical and mechanical restrictions needed for high-speed motors. Most solid rotors have temperature rise higher than bearing temperature restrictions and another bearing type would have to be used if for example a slitted rotor is to be utilized. If another bearing type would be utilized also the whole tolerance system of the other motor parts would change, since the tolerance recommendations comes from the bearing supplier.

10.3 CONCLUSION

High-speed technology has made it possible to eliminate gear boxes used in traditional high-speed systems. This leads to advantages such as improvement of over-all efficiency and reliability. High-speed systems need machine elements capable of withstanding the centrifugal forces and high rotational speed. High-speed systems are used in numerous industrial applications requiring high speed, e.g. compressors, turbochargers and blowers. There is a growing demand for cost efficient high-speed motors in the market. Production lines for high-speed motors do not exist yet; this would be the next step in the development.

High operational speed primarily sets requirements on bearings, bearing support parts, rotor and cooling of the motor. There are several alternatives to bearings; active magnet bearings, gas foil bearings and hybrid ceramic bearings. Magnet bearings would be the best alternative but to date they are very expensive. Currently some kind of hybrid bearings is the most feasible alternative. In the high-speed prototype motor hybrid ceramic bearings are used, but these set requirements for rotor design. There are also several alternatives and combinations for rotor design, among the rotor alternatives the most suitable for the high-speed motor in question would be a conventional laminated rotor, copper coated solid rotor or a slitted solid rotor or a combination of a slitted and copper coated rotor. The rotor is the most challenging part for redesign since a design trade off needs to be made regarding producing a rotor at low cost versus keeping the electrical properties at a sufficient level.

Table 4 depicts the cost cutting potential for each machine element and the alternations necessary for the lowered cost.

Table 4. Cost cutting potential and alternations necessary for the different machine elements.

	Rotor	**Bearing covers**	**Bearing end shields**	**Stator frame foot**	**Bearings**	**Stator frame**	**Stator sheets**
Cost cutting potential	50 %	96 %	90 %		20 %	94 %	95 %
Alternations necessary	producing a laminated rotor with support clamps instead of a copper coated rotor	tolerances need to be altered	the stator frame foot should be integrated with bearing end shields, made from cast iron		high-speed hybrid bearings will also be used in serial production	standard stator frame producing methods will be used	stator sheet cutting equipment needs to be purchased for the stator sheet size in question

The cost cutting potential for the machine components are substantial, but here one needs to keep in mind that solely going for mass production methods creates a cost cut. The cost of producing the different parts also depends on suppliers having different price levels. Regarding the bearing support parts quality tradeoff has been done to lower production costs, whilst it was decided to use different production methods for the bearing end shields and the stator frame.

10.4 RECOMMENDATIONS FOR FURTHER WORK

Further product development is needed to develop a functioning high-speed motor with inexpensive parts suitable for serial production. A high-speed motor with a laminated squirrel cage rotor could be produced and this might be the first hand option in serial production. Although designing of the rotor requires extra attention for the end ring material and end ring support clamps are needed.

Testing of the Hot Isostatic Pressing Copper coated method should be conducted to conclude if the method would work in practice, since this method would be a good serial production method of a copper layer of the right thickness.

Further development of the slitted rotor, more prototypes and testing should be conducted to see if this rotor could somehow be an option for using in a high-speed serial produced motor. A slitted rotor in combination with copper coating might be a feasible option in combination with another bearing type.

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